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TRANSMITTAL LETTER TO THE UNITED STATES DESIGNATED/ELECTED OFFICE (DO/EO/US) CONCERNING A FILING UNDER 35.U.S.C. 371

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INTERNATIONAL APPLICATION NO PCT/AU99/00409	INTERNATIONAL FILING DATE 26 MAY 199	PRIORITY DATE CLAIMED 26 MAY 1998

TITLE OF INVENTION
DATA TRANSMISSION AND RECEPTION IN MULTICARRIER MODULATION SYSTEMS

APPLICANT(S) FOR DO/EO/US
Jean Armstrong

Applicant herewith submits to the United States Designated /Elected Office (DO/EO/US) the following items and other information:

1. [x] This is a FIRST submission of items concerning a filing under 35 U.S.C. 371.
2. [ ] This is a SECOND or SUBSEQUENT submission of items concerning a filing under 35 U.S.C. 371.
3. [x] This express request to begin national examination procedures (35 U.S.C. 371(f)) at any time rather than delay examination until the expiration of the applicable time limit set in 35 U.S.C. 371(b) and PCT Articles 22 and 39(I).
4. [ ] A proper Demand for International Preliminary Examination was made by the 19th month from the earliest claimed priority date.
5. [ ] A copy of the International Application as filed (35 U.S.C. 371(c)(2))
    a. [ ] is transmitted herewith (required only if not transmitted by the International Bureau).
    b. [ ] has been transmitted by the International Bureau.
    c. [ ] is not required, as the application was filed in the United States Receiving Office (RO/US).
6. [ ] A translation of the International Application into English (35 U.S.C. 371(c)(2)).
7. [ ] Amendments to the claims of the International Application under PCT Article 19 (35 U.S.C. 371(c)(3))
    a. [ ] are transmitted herewith (required only if not transmitted by the International Bureau).
    b. [ ] have been transmitted by the International Bureau
    c. [ ] have not been made; however, the time limit for making such amendments has NOT expired.
    d. [ ] have not been made and will not be made.
8. [ ] A translation of the amendments to the claims under PCT Article 19 (35 U.S.C. 371(c)(3)).
9. [ ] An oath or declaration of the inventor(s) (35 U.S.C. 371(c)(4)).
10. [ ] A translation of the annexes to the International Preliminary Examination Report under PCT Article 36 (35 U.S.C. 371(c)(5)).

Items 11. to 16. below concern other document(s) or information included:

11. [ ] An Information Disclosure Statement under 37 CFR 1.97 and 1.98.
12. [ ] An assignment document for recording. A separate cover sheet in compliance with 37 CFR 3.28 and 3.31 is included.
13. [x] A FIRST preliminary amendment.
    [ ] A SECOND or SUBSEQUENT preliminary amendment.
14. [ ] A substitute specification.
15. [ ] A change of power of attorney and/or address letter.
16. [x] Other items or information:

WO99/62207 International Publication (including 18 sheets drawings)
International Search Report
International Preliminary Examination Report
PCT Request
PCT Demand

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INTERNATIONAL APPLICATION NO	INTERNATIONAL FILING DATE	PRIORITY DATE CLAIMED
PCT/AU99/00409 09/701222	26 MAY 1999	26 MAY 1998

17. [X] The following fees are submitted:

	CALCULATIONS	PTO USE ONLY
Basic National Fee (37 CFR 1.492(a)(1)-(5):		
Neither international preliminary examination fee (37 CFR 1.482) Nor international search fee (37 CFR 1.445(a)(2)) paid to USPTO and International Search Report not prepared by the EPO or JPO (1.492(a)(3)) $1,000.00		
International preliminary examination fee (37 CFR 1.482) not paid to USPTO but International Search Report prepared by the EPO or JPO (1.492(a)(5) $860.00		
International preliminary examination fee (37 CFR 1.482) not paid to USPTO but international search fee (37 CFR 1.445(a)(2)) paid to USPTO(1.492(a)(2)) $710.00		
International preliminary examination fee paid to USPTO (37 CFR 1.482) but all claims did not satisfy provisions of PCT Article 33(1)-(4) (1.492(a)(1)) $690.00		
International preliminary examination fee paid to USPTO (37 CFR 1.482) and all claims satisfied provisions of PCT Article 33(1)-(4) . . . . $ 100.00		
ENTER APPROPRIATE BASIC FEE AMOUNT =	$860.00	
Surcharge of $130.00 for furnishing the oath or declaration later than **[ ] 20 [ ] 30** months from the earliest claimed priority date (37 C.F.R. 1.492)(e)).	$	

Claims	Number Filed	Number Extra	Rate	$	
Total Claims	37 -20=	17	X $ 18.00	$306.00	
Independent Claims	4 -3=		X $ 80.00	$ 80.00	
Multiple dependent claim(s) (if applicable)			+ $270.00	$	
TOTAL OF ABOVE CALCULATIONS =				$1246.00	
Reduction by ½ for filing by small entity, if applicable. Verified Small Entity statement must also be filed. (Note 37 CFR 1.9, 1.27, 1.28).				$623.00	
SUBTOTAL =				$623.00	
Processing fee of $130.00 for furnishing the English translation later than **[ ] 20 [ ] 30** months from the earliest claimed priority date (37 CFR 1.492(f)). +				$	
TOTAL NATIONAL FEE =				$623.00	
Fee for recording the enclosed assignment (37 CFR 1.21(h)). The assignment must be accompanied by an appropriate cover sheet (37 CFR 3.28, 3.31). $40.00 per property +				$	
TOTAL FEES ENCLOSED =				$623.00	
				Amt. refunded	$
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a. [X] A check in the amount of $ 623.00 to cover the above fees is enclosed.

b. [ ] Please charge our Deposit Account No. 02-4377 in amount of $___ to cover the above fees. A copy of this sheet is enclosed.

c. [X] The Commissioner is hereby authorized to charge any additional fees which may be required, or credit any overpayment to Deposit Account No. 02-4377. A copy of this sheet is enclosed.

NOTE: Where an appropriate time limit under 37 CFR 1.494 or 1.495 has not been met, a petition to revive (37 CFR 1.137(a) or (b)) must be filed and granted to restore the application to pending status.

SEND ALL CORRESPONDENCE TO:

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November 27, 2000
Date

19,498
Registration No.

09/701222

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PATENT

IN THE UNITED STATES PATENT AND TRADEMARK OFFICE

Applicant	:	Jean Armstrong
Serial No.	:	To be assigned
Filed	:	To be assigned
For	:	DATA TRANSMISSION AND RECEPTION IN MULTICARRIER MODULATION SYSTEMS

PRELIMINARY AMENDMENT

Express Mail Mailing No. **EK839856586US**

Assistant Commissioner of Patent
Box Patent Application
Washington, D.C., 20231

Sir or Madam:

Preliminary to the examination of this application, please enter the following amendments:

In the Claims:

Cancel claims 1 - 35.

Please add the following new claims:

36. A method of transmitting data in a multicarrier modulation system in which transform pairs allow communication using multiple subcarriers, the method including:

modulating representations of the data on groups of subcarriers; and introducing a predetermined amount of intersymbol interference between symbols;

wherein the modulating includes a modulation operation in which the data is effectively multiplied with weighting factor, before performing an inverse transformation.

37. A method as claimed in claim 36, wherein the modulation operation includes a windowing operation in which the data is multiplied with a complex window after the performing of the inverse transformation.

38. A method as claimed in claim 36, wherein the groups of subcarriers include non-overlapping sets of M adjacent subcarriers, and the representations of data include M respective integer multiples of the data, the integer multiples corresponding to coefficients of an expanded polynomial expression: $(1-x)^{M-1}$.

39. A method as claimed in claim 36, wherein the data is modulated on a pair of adjacent subcarriers and the representations of the data are multiples of 1 and -1.

40. A method as claimed in claim 36, wherein the introducing of a predetermined amount of intersymbol interference includes overlapping successive symbols to a predetermined extent by delaying and summing groups of samples of the symbols.

41. A method as claimed in claim 40, wherein successive symbols are overlapped with each other by half a symbol period.

42. A method as claimed in claim 36, wherein inverse transformation includes using mathematical correlations between representations of the data to reduce hardware requirements, hardware requirements including computational and memory requirements

on which the inverse transformation is determined.

43. A method as claimed in claim 42, wherein the performing of the inverse transformation is performed at least in part by a complex windowing operation.

44. A method as claimed in claim 36, wherein the groups of subcarriers are modulated by a summation of representations of different data.

45. A method as claimed in claim 44; wherein each subcarrier is modulated by a difference between adjacent data.

46. A method as claimed in claim 36, further including providing pilot tones on subcarriers.

47. A method as claimed in claim 46, wherein relative values of the pilot tones on successive symbols follows a sequence comprising +1, 0, +1, 0, -1, 0, -1, 0.

48. A method of receiving data in a multicarrier modulation system in which transform pairs allow communication using multiple subcarriers, the method including:

demodulating the data from representations of data on groups of subcarriers; and

removing a predetermined amount of intersymbol interference between symbols;

wherein the demodulating includes a demodulation operation in which the representations are multiplied with weighting factors, the results are summed, and a transformation is performed.

49. A method as claimed in claim 48, wherein the demodulation operation includes a complex windowing operation in which the representations are multiplied

with a complex window before the transformation.

50. A method as claimed in claim 48, wherein the groups of subcarriers include non-overlapping sets of M adjacent subcarriers, and the representations of data include M respective integer multiples of the data, the integer multiples corresponding to coefficients of an expanded polynomial expression: $(1 - x)^{M-1}$.

51. A method as claimed in claim 48, wherein the data is modulated on a pair of adjacent subcarriers, and the representations of the data are multiples of 1 and -1.

52. A method as claimed in claim 48, wherein the removing of the predetermined amount of intersymbol interference between symbols includes removing a predetermined amount of intersymbol interference caused by overlapping symbols to a predetermined extent.

53. A method as claimed in claim 52, wherein the predetermined amount of intersymbol interference is provided by overlapping symbols by half a symbol period.

54. A method as claimed in claim 48, wherein the removing of the predetermined amount of intersymbol interference between symbols includes delaying groups of samples so that each transformation operates on samples which reduce an error rate.

55. A method as claimed in claim 48, wherein the removing of the predetermined amount of intersymbol interference between symbols includes frequency domain equalization.

56. A method as claimed in claim 55, wherein the frequency domain equalization includes an operation using relatively few significant terms owing to the use of groups of subcarriers modulated by representations of the data.

57. A method as claimed in claim 55, wherein the frequency domain equalization includes providing calculations which are the same for each subcarrier.

58. A method as claimed in claim 55, wherein the frequency domain equalization operates on the output of the demodulation.

59. A method as claimed in claim 48, wherein the removing of the intersymbol interference includes a fixed operation for removing intersymbol interference caused by introduction of the predetermined amount of intersymbol interference, and an adaptive operation for removing intersymbol interference caused by factors other than introduction of the predetermined amount of intersymbol interference.

60. A method as claimed in claim 48, wherein the transformation includes using mathematical correlations between representations of the data to reduce hardware requirements, hardware requirements including computational and memory requirements, on which the transformation is determined.

61. A method as claimed in claim 60, wherein said transformation includes complex windowing removing operation.

62. A method as claimed in claim 48, further including symbol synchronization involving measuring the correlation between sections of signal, in which pilot tones are provided on subcarriers.

63. A method as claimed in claim 62, wherein relative values of the pilot tones on successive symbols follows a sequence comprising +1, 0, +1, 0, -1, 0, -1, 0.

64. A method as claimed in claim 48, further including frequency synchronization involving measuring phase changes between the pilot tones provided on subcarriers.

65. A method as claimed in claim 48, further including frequency synchronization involving calculating a metric having a known dependence on frequency offset.

66. A method as claimed in claim 65, wherein the metric approximates the multiplicative product of frequency offset and symbol period according to an expression:

$$\mathrm{Re}\left(\frac{y_{k,l}+y_{k+1,l}}{y_{k,l}-y_{k+1,l}}\right).$$

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67. A transmitter suitable for transmitting data in a multicarrier modulation system in which transform pairs allow communication using multiple subcarriers, the transmitter including:

means for modulating representations of data on groups of subcarriers; and

means for introducing a predetermined amount of intersymbol interference between symbols;

wherein the modulation includes a modulation operation in which the data is multiplied with weighting factor, before an inverse transformation.

68. A transmitter as claimed in claim 67, wherein the means for modulating includes a complex windowing operation in which the data is multiplied with a complex window after inverse transformation.

69. A receiver suitable for receiving data in a multicarrier modulation system in which transform pairs allow communication using multiple subcarriers, the receiver including:

means for demodulating data from representations of data on groups of subcarriers; and

means for removing a predetermined amount of intersymbol interference between symbols;

wherein the means for demodulating includes a demodulation operation in which the representations are multiplied with weighting factors, the results are summed, and a transformation is performed.

70. A receiver as claimed in claim 37, wherein the demodulation includes a complex windowing operation in which the representations are multiplied with a complex window, before the transformation.

71. A multicarrier modulation system incorporating one or more transmitters as claimed in claim 67 and one or more receivers as claimed in claim 69, wherein the transmitters and receivers are adapted to communicate with each other.

72. A multicarrier modulation system as claimed in claim 71, wherein the weighting factors respectively used in the transmitter and the receiver have equal relative values, or the complex windows respectively used in the transmitter and the receiver are

the complex conjugate of each other.

REMARKS

Claims 1 - 35 have been canceled and replaced with new claims 36 - 72. Claims 36 - 72 reflect amendments to claims 1 - 35, which put these claims in conformance with United States patent practice. No new matter has been introduced.

Entry of these Amendments and an early examination on the merits are respectfully requested.

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Respectfully submitted,

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Dated: November 27, 2000

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DATA TRANSMISSION AND RECEPTION IN MULTICARRIER MODULATION SYSTEMS

Field of the invention

The invention relates to data transmission and reception in multicarrier modulation systems which use orthogonal transform pairs to allow communication on multiple subcarriers.

Background of the invention

Multicarrier modulation systems operate by dividing a serial data stream into several parallel component data streams, and transmitting each of these parallel data streams on separate subcarriers. At the receiving end, each of the parallel data streams is received, and arranged into a serial data stream corresponding with the serial data stream provided to the transmitter. Accordingly, in this type of system, only a small proportion of the total data is carried on each subcarrier.

While the power spectrum of each of the parallel data streams overlaps, communication is possible as the subcarriers are generally orthogonal with each other over a symbol period. This is a direct consequence of the use of orthogonal transforms in the transmitter and receiver respectively. Using an *N*-point transform (and thus providing *N* subcarriers) effectively increases the symbol period by a factor of *N*.

There are various design issues which limit the practical application of multicarrier modulation systems.

Multicarrier modulation systems are generally sensitive to multipath effects, and are particularly sensitive to differences in the frequency of the local oscillators at the transmitter and receiver. Multicarrier modulation systems are also sensitive to Doppler effects which are unavoidable in mobile and satellite applications.

Furthermore, multicarrier modulation systems suffer a lack of bandwidth

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containment, as the power spectrum roll-off is of the form $1/(f^2 N)$ where f is the frequency and N is number of subcarriers. The roll-off characteristics can be improved by increasing the number of subcarriers N, but this does not change the form of the roll-off. This gradual roll-off means that multicarrier modulation signals must be sufficiently spaced in the frequency domain from other signals to avoid interference. However, this is unsatisfactory as it (a) does not alter the form of the power roll-off, (b) increases intercarrier interference due to increased sensitivity to frequency offsets, and (c) increases the computational complexity associated with the orthogonal transform.

Zhao and Häggman suggest using two representations of the input data (one the negative of the other) in order to reduce intercarrier interference ("Sensitivity to Doppler Shift and Carrier Frequency Errors in OFDM Systems - The Consequences and Solutions" *IEEE 46th Vehicular Technology Conference*, Atlanta, April 1996, pp. 1563-1568). However, this technique is not bandwidth efficient.

It is an object of the invention to alleviate at least in part one or more of the problems of the prior art. More particularly, embodiments of the invention attempt to provide a multicarrier modulation communication system which improves out-of-band power leakage, and the effect of intercarrier and intersymbol interference, while maintaining or increasing bandwidth efficiency.

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Summary of the invention

The invention provides a method of transmitting data in a multicarrier modulation system in which transform pairs allow communication using multiple subcarriers, the method including:

modulating representations of data on groups of subcarriers; and

introducing a predetermined amount of intersymbol interference between symbols.

The invention also provides a method of receiving data in a multicarrier modulation system in which transform pairs allow communication using multiple subcarriers, the method including:

demodulating data from representations of data on groups of subcarriers; and

removing a predetermined amount of intersymbol interference between symbols.

Furthermore, the invention correspondingly provides a transmitter and a receiver respectively including means capable of performing the inventive methods of transmitting and receiving data, as described above. The invention also provides a multicarrier modulation system including one or more such transmitters and one or more such receivers.

Preferably, introducing a predetermined amount of intersymbol interference is provided by overlapping symbols in the time domain. Preferably, this is achieved by selectively delaying and summing adjacent groups of symbols.

Modulation of subcarriers can be achieved using weighting techniques or alternatively windowing techniques.

Embodiments of the invention are applicable to multicarrier modulation systems that use any suitable scheme to modulate subcarriers. For example, phase-shift keying or quadrature amplitude modulation can be used. In principle, embodiments can use modulation schemes that are suitable for multicarrier modulation systems generally.

Embodiments of the invention are applicable to input data having an arbirary statistical distribution. For instance, the input data may be previously coded using an error correcting code, by source coding or by any other relevant coding scheme, for example, code division multiple access (CDMA).

Embodiments of the invention are suitable for terrestrial as well as wireless systems. Various applications of particular embodiments include: (a) digital transmission over the public telephone network (for example, asymmetric digital subscriber loop (ADSL) and high-rate digital subscriber line (HDSL)) (b) digital audio broadcasting (c) digital mobile telephony (d) digital television broadcasting (e) satellite communications (f) wireless local area networks. Other applications, such as in relation to high bandwidth data storage technologies are also possible. While embodiments of the invention are described in relation to carrier systems, the principles of the invention are also applicable to baseband systems.

Embodiments of the invention are described in relation to orthogonal frequency division multiplexing (OFDM) systems, which are a particularly popular type of multicarrier system in which discrete Fourier transforms are used to provide subcarriers which are equally spaced in the frequency domain.

Description of drawings

Fig. 1 is a schematic diagram of a known OFDM system.

Fig. 2 is a graph representing the power roll-off of a typical prior art OFDM system. The x-axis is in frequency and the y-axis is in decibels (dB).

Fig. 3 is a graph representing the complex interference coefficients demonstrating the interference characteristics of a typical prior art OFDM system in the presence of typical values of carrier frequency offset. In this example $\Delta fT = 0.2$ and $N = 16$, with phase-offset equal to zero at the beginning of the symbol period. The real components of the complex interference coefficients are represented by diamonds and the imaginary components are represented by triangles.

Fig. 4 is a schematic diagram of a transmitter in accordance with an embodiment of the invention.

Fig. 5 is a schematic diagram of part of the transmitter shown in Fig. 4.

Fig. 6 is a schematic diagram of a receiver in accordance with an embodiment of the invention.

Fig. 7 is a schematic diagram of the delay means of the receiver shown in Fig. 6.

Figs. 8 and 9 are schematic diagrams of parts of an estimation means of the receiver shown in Fig. 6.

Fig. 10 is a schematic diagram of a transmitter and receiver which use a windowing technique to modulate and demodulate representations of input data to and from subcarriers.

Fig. 11 is a schematic diagram of a transmitter and receiver which use an alternative windowing technique to modulate and demodulate representations of input data to and from subcarriers.

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Fig. 12 is a schematic diagram of a transmitter which uses three representations of input data to modulate subcarriers.

Fig. 13 is a schematic diagram of a transmitter which uses a general mapping of subcarriers to modulate subcarriers.

Figs. 14 to 16 are scatterplots representing symbols received for OFDM systems having 64 subcarriers using respectively no cancellation (conventional system), linear cancellation and cubic cancellation.

Fig. 17 is a graph representing the signal to intercarrier interference (ICI) noise ratio of an embodiment of the invention compared with the signal to ICI noise ratio of a conventional OFDM system. The y-axis is in decibels (dB) and the x-axis is in frequency offset as a proportion of the spacing between subcarriers. The upper curve is representative of a performance curve for an embodiment of the invention that provides cubic cancellation. The lower curve is representative of a performance curve for a conventional OFDM system.

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Fig. 18 includes an upper graph representing the power spectrum roll-off of a conventional OFDM system, and a lower graph representing the power spectrum roll-off of an embodiment of the present invention. In both graphs the x-axis is in frequency and the y-axis is in decibels (dB).

Guide to terms and symbols

The following notation is used throughout the description in relation to various equations.

T	symbol period of symbol on input data channels
N	size of an orthogonal transform
P	number of weighted input data
D	number of input data in symbol period
W	number of weighting coefficients for each input data
$d_{0,i}\ldots d_{D-1,i}$	input data of i-th symbol at input to weighting means

$K_0 \ldots K_{D-1}$	transmitter pre-weighting coefficients
$p_0 \ldots p_{W-1}$	transmitter weighting coefficients
$g_1 \ldots g_{W-1}$	transmitter generating polynomial coefficients
$a_{0,i} \ldots a_{N-1,i}$	weighted input data of i-th symbol, at output of weighting means and input to orthogonal transform
$c_{0,j} \ldots c_{N-1,j}$	transmitter transform output data at output of orthogonal transform
$N-m$	number of samples by which overlapping symbols are overlapped in the time domain
s_k	transmitter aggregate data at output of parallel-to-serial converter and input to digital-to-analog converter
$s(t)$	transmitter baseband signal
$u(t)$	analog transmission signal
f_c	transmitter local oscillator frequency
$\exp(j2\pi f_c t)$	transmitter local carrier signal
f_r	receiver local oscillator frequency
$\exp(j2\pi f_r t)$	receiver local carrier signal
Δf	local oscillator frequency difference
$v(t)$	analog reception signal
$r(t)$	receiver baseband signal
r_k	receiver aggregate data at output of analog-to-digital converter
$x_{0,j} \ldots x_{N-1,j}$	receiver transform input data of i-th symbol input to orthogonal transform
$y_{0,i} \ldots y_{N-1,i}$	receiver transform output data of i-th symbol at output of orthogonal transform
$v_{0,i} \ldots v_{D-1,i}$	receiver demodulator data of i-th symbol at output of weighting means
$q_0 \ldots q_{W-1}$	receiver weighting coefficients
$e_{0,i} \ldots e_{D-1,i}$	output data of i-th symbol at output of estimator
$C_0 \ldots C_{N-1}$	complex interference coefficients

Description of embodiments

Fig. 1 shows a known OFDM system. This type of transmission system was developed in order to provide a high-data bandwidth efficient system for data transmission. The basic principle is to allow the spectra of the subchannels of the data transmission system to overlap in order to make better use of the available bandwidth. Overlapping subcarrier spectra is possible as the signal carried by each subcarrier is mathematically orthogonal to each other over a symbol period as a result of the use of an orthogonal transform 3 such as a discrete Fourier transform (DFT).

In reference to Fig. 1, input data $d_{0,i}$ ... $d_{N-1,i}$ to be transmitted is directly input to an orthogonal transform 3, the output of which is transmitter transform output data $c_{0,i}$ ... $c_{N-1,i}$ that is input directly to a parallel-to-serial converter 7. The parallel-to-serial converter 7 produces transmitter aggregate data s_k that is a linear sequence of values appropriate for transmission. The parallel-to-serial converter 7 produces transmitter aggregate data s_k on a transmitter aggregate data channel.

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The serial output is termed transmitter aggregate data s_k that is then input to a digital-to-analog converter (DAC) 8. The output from the DAC 8 is then a transmitter baseband signal $s(t)$.

This transmission channel can be any appropriate channel, and the characteristics of the analog transmission signal $u(t)$ are chosen to accommodate the transmission channel.

The receiver receives the analog transmission signal $u(t)$ as an analog reception signal $v(t)$, and in this sense the analog reception signal $v(t)$ corresponds with the analog transmission signal $u(t)$. Of course, in the prior art systems as in embodiments of the invention, these signals are not identical except in an ideal, noiseless transmission channel. In real systems, the analog reception signal $v(t)$ is a noisy, distorted representation of the analog transmission signal $u(t)$.

The receiver receives the analog reception signal $v(t)$ and multiplies it by a receiver local carrier signal $\exp(j2\pi f_r t)$ 10 to obtain a receiver baseband signal $r(t)$. This receiver baseband signal $r(t)$ is input to a analog-to-digital converter (ADC)

11. The output of the ADC 11 provides receiver aggregate data r_k which is input to a serial-to-parallel converter 12 that provides receiver transform input data $x_{0,i}$ ... $x_{N-1,i}$ to an orthogonal transform 16. The orthogonal transform 16 then provides output data $e_{0,i}$ ... $e_{N-1,i}$ that corresponds with the input data $d_{0,i}$ ... $d_{N-1,i}$.

In the prior art as in embodiments of the invention, the orthogonal transforms 3 and 16 in the transmitter and receiver respectively, are the inverse of each other. Conceptually, it is considered that the orthogonal transform 3 in the transmitter is an inverse transform to provide a mapping from the frequency domain to the time domain and the orthogonal transform 16 in the receiver is a forward transform to provide a mapping from the time domain back to the frequency domain.

In an ideal system, the output data $e_{0,i}$ ... $e_{N-1,i}$ is precisely equal to the input data $d_{0,i}$ ... $d_{N-1,i}$. However, as previously outlined, this is not the case in practical systems as are known in the prior art.

In an OFDM receiver, the analog reception signal $v(t)$ is translated down to baseband to produce the receiver baseband signal $r(t)$. If the other carriers all beat down to frequencies that, in the time domain, have a whole number of cycles in the symbol period (T), there is zero contribution from all these other subcarriers. Thus the subcarriers are mathematically orthogonal if the subcarrier spacing is a multiple of 1/T. This condition is a natural result of using an orthogonal transform pair 3 and 16 such as a IDFT and DFT in the transmitter and receiver respectively.

Known OFDM systems such as that described above, are deficient as earlier outlined. Fig. 2 demonstrates the power spectra of an OFDM signal which demonstrates the lack of bandwidth containment of the known OFDM system shown in Fig. 1.

Fig. 3 is a graph of complex interference coefficients ($C_0 \ldots C_{N-1}$) for illustrative values of frequency offset ($\Delta fT = 0.2$ and $N = 16$, with phase-offset equal to zero at the beginning of the symbol period). Frequency offset Δf can arise due to absolute differences in the frequencies f_c and f_r of local oscillators in the transmitter and receiver respectively, and by Doppler shifts due to relative motion

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of transmitter and receiver. Frequency offset results in ICI, which is quantatively indicated by complex interference factors.

In Fig. 3, real components of the complex interference coefficients are represented by diamonds and the imaginary components are represented by triangles. ICI may be interpreted in terms of the complex interference coefficients ($C_0 ... C_{N-1}$) that measure the contribution of a transmitter subcarrier to each demodulated subcarrier; that is, the interference in one subcarrier arising from effects between subcarriers.

As can be seen from Fig. 3, the complex interference coefficients ($C_0 ... C_{N-1}$) vary smoothly between subcarriers except at the transitions from the reference subcarrier (whose impact on other subcarriers is being measured) to its immediately adjacent subcarriers.

It is observed that the form of variation of complex interference coefficients ($C_0 ... C_{N-1}$) across subcarriers can be closely modelled by a relatively low order polynomial equation. This predictability allows for generally consistent cancellation of ICI by modulating groups of subcarriers with representations of the data.

An example embodiment of the invention is now described in relation to Fig. 4 and Fig. 5.

Fig. 4 shows a transmitter in accordance with an embodiment of the invention. Compared with the OFDM system shown in Fig. 1, the transmitter shown in Fig. 4 provides for modulating representations of data on groups of subcarriers, and introducing a substantially predetermined amount of intersymbol interference between symbols.

The input data ($d_{0,i} ... d_{D-1,i}$) is provided on input data channels. Representations of the input data are modulated onto groups of subcarriers by multiplying each input data through a weighting means 1 to provide weighted input data which is then input to an orthogonal transform 3. In Fig. 4, the weighting means 1 includes what are represented as a collection of the transmitter weighting coefficients (p_0 and

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p_1). Each input data ($d_{0,i}$ ... $d_{D-1,i}$) on the input data channels is multiplied by transmitter weighting coefficients (p_0 and p_1) in order to generate two weighted representations of each of the input data ($d_{0,i}$ ... $d_{D-1,i}$). Collectively these weighted representations of the input data ($d_{0,i}$ ... $d_{D-1,i}$) are the weighted input data ($a_{0,i}$ ... $a_{N-1,i}$) which are used to modulate two adjacent subcarriers. It is not necessary that every subcarrier be used. (For example, in baseband applications, it is necessary that the input to the transform have Hermitian symmetry so that the output has no imaginary components.) Rather, every subcarrier should be paired with an oppositely weighted subcarrier. Preferably, paired subcarriers are adjacent to each other.

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The orthogonal transform 3 has N inputs that directly correspond with the number of subcarriers N modulated by representations of the input data, in this case the weighted input data. Each output of the orthogonal transform 3 in the transmitter corresponds with a transmitter transform output data channel.

Fig. 5 shows the interaction of a delay means 6 and the parallel-to-serial converter 7. Half of the transmitter transform output data from the orthogonal transform 3 is passed to a delay means 6 which together with parallel-to-serial converter 7 and the addition operation introduces a known and predetermined amount of intersymbol interference between symbols. The first N/2 elements of the transmitter transform output data are converted to serial form, while the second N/2 elements are first delayed by T/2 before parallel-to-serial conversion. Each delayed output data is summed with a non delayed output, so that each transmitter aggregate data is the summation of two samples from adjacent symbols.

Accordingly, each transmitter aggregate data is the summation of two terms from adjacent symbols. The table below shows the relationship between the aggregate data and the transmitter transform output data for an overlap of T/2.

$c_{4,i-1}$	$c_{5,i-1}$	$c_{6,i-1}$	$c_{7,i-1}$								
$c_{0,i}$	$c_{1,i}$	$c_{2,i}$	$c_{3,i}$	$c_{4,i}$	$c_{5,i}$	$c_{6,i}$	$c_{7,i}$				
				$c_{0,i+1}$	$c_{1,i+1}$	$c_{2,i+1}$	$c_{3,i+1}$	$c_{4,i+1}$	$c_{5,i+1}$	$c_{6,i+1}$	$c_{7,i+1}$
								$c_{0,i+2}$	$c_{1,i+2}$	$c_{2,i+2}$	$c_{3,i+2}$
s_k	s_{k+1}	s_{k+2}	s_{k+3}	s_{k+4}	s_{k+5}	s_{k+6}	s_{k+7}	s_{k+8}	s_{k+9}	s_{k+10}	s_{k+11}

In this example, N is 8 for simplicity. Considering the i-th transform output data, the first N/2 elements are added term by term to the last N/2 elements of the (i-1) th transmitter transform output data, for example, $c_{0,i}$ is added to $c_{N/2,i-1}$, $c_{1,i}$ is added to $c_{N/2+1,i-1}$ and so on. Similarly the last N/2 elements are added term by term to the first N/2 elements of the (i+1)*th* transmitter transform output data.

There are three operations involved in converting the transmitter transform output data to the aggregate data. These are delaying, adding and parallel-to-serial conversion. Of course, these operations need not necessarily be this order. The delaying and adding operations can either occur before or after the parallel-to-serial conversion. Alternatively, delaying can occur before parallel-to-serial conversion, with adding occuring after parallel-to-serial conversion.

In the embodiment shown in Fig. 4, and its delay means 6 shown in Fig. 5, successive symbol interferes with each other by half a symbol period. However, there are other ways in which intersymbol interference can be introduced in this way. For example, it is possible to use a general overlap of N-m samples between adjacent symbols. A new symbol begins transmission every mT/N seconds. Thus, if more than two symbols overlap, each transmitter aggregate data correspondingly involves a summation including more terms. If m = N/4, then four symbols are added, and four values summed. A similar delay means 6 and parallel-to-serial converter 7 as shown in Fig. 5 can be used, with modifications as appropriate.

Introducing intersymbol interference by overlapping adjacent symbols has the advantage of improving the distribution of instantaneous signal amplitudes in the transmitted signal. Using an overlap of T/2 results in a constant amplitude envelope. Progressively increasing the amount of intersymbol interference increases the data rate, but also increases the complexity of the receiver, and increases the effect of added noise in the transmission channel.

The transmitter aggregate data s_k produced by the parallel-to-serial conveter 7 is passed through a digital-to-analog converter 8 to produce a transmitter baseband signal $s(t)$.

Fig. 6 shows a receiver corresponding with the transmitter shown in Fig. 4. Two operations are required: demodulating the groups of subcarriers and removing the intersymbol interference. Delay means 15 in combination with orthogonal transform 16 and weighting means 17 can be considered to provide demodulation, while storage means 18 and equaliser 19 can be considered to remove intersymbol intereference.

In Fig. 6, the receiver aggregate data r_k is input to a delay means 15 that outputs receiver transform input data ($x_{0,i}...x_{N-1}$). The delay means 15 is used to provide the orthogonal transform 16 with different combinations of receiver delay data so that the output data can be subsequently weighted and added using weighting means 17 as described below. The weighting means 17 weights and sums the receiver transform output data. The coefficients $q0$, $q1$ used in the weighting means 17 are preferably the same as $p0$, $p1$ as discussed below.

Fig. 7 shows the delay means 15 in Fig. 6 in more detail. The delay means 15 is designed to achieve symbol synchronisation with the aim of reducing error rate after equalisation. An N-stage shift register 15B is used to hold the data delayed by delay means 15A so that the receiver transform input data presented to the orthogonal transform 16 represents N successive values of the receiver delay data. The data is then shifted N/2 stages up the shift register before the next orthogonal transform is performed.

r_k	r_{k+1}	r_{k+2}	r_{k+3}	r_{k+4}	r_{k+5}	r_{k+6}	r_{k+7}	r_{k+8}	r_{k+9}	r_{k+10}	r_{k+11}
$x_{4,i-1}$	$x_{5,i-1}$	$x_{6,i-1}$	$x_{7,i-1}$								
$x_{0,i}$	$x_{1,i}$	$x_{2,i}$	$x_{3,i}$	$x_{4,i}$	$x_{5,i}$	$x_{6,i}$	$x_{7,i}$				

$x_{0,i+1}$	$x_{1,i+1}$	$x_{2,i+1}$	$x_{3,i+1}$	$x_{4,i+1}$	$x_{5,i+1}$	$x_{6,i+1}$	$x_{7,i+1}$
				$x_{0,i+2}$	$x_{1,i+2}$	$x_{2,i+2}$	$x_{3,i+2}$

For example, consider the case of N=8 as shown in the above table. The delay means 15 operates to output the receiver aggregate data r_k ... r_{k+7}, as the receiver transform input data $x_{0,i}$ ... $x_{7,i}$. The transform input data are the values that transform 16 uses for the i-th transform operation. Once this has occurred, r_{k+4} ... r_{k+7} are shifted up the register and values r_{k+8} ... r_{k+11} are shifted in. The (i+1)-th transform operation is then performed using output receiver aggregate data r_{k+4} ... r_{k+11}, as the receiver transform input data $x_{0,i+1}$ ... $x_{7,i+1}$. Thus receiver transform operations are performed at intervals T/2. For the case of perfect synchronisation and no distortion and no noise in the channel, $r_k = s_k$. This means that all of the values of r_k which depend on the transmitter transform output data $c_{0,i}$ ... $c_{N-1,i}$ which are the results of the i-th transmitter transform are used as input to the i-th receiver transform.

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In practice distortion in the channel will mean that , $r_k \neq s_k$ and that more than N samples of the receiver aggregate data depend on $c_{0,i}$ ... $c_{N-1,i}$. In this case the symbol synchronisation circuits operate to minimise the error rate after equalisation.

Fig. 7 shows the symbol synchronisation being achieved by a variable delay. In practice, symbol synchronisation can also be achieved by varying the sampling instants of the ADC and/or by controlling the clocking of data into the shift register 15B.

Embodiments of the invention do not use cyclic prefixes to avoid intersymbol interference, and accordingly it is not possible to achieve symbol synchronisation or frequency synchronisation by using correlations between the cyclic prefix and the symbol. Instead, it is appropriate to use other methods which use pilot tones, or which are blind estimation techniques based on the properties of the modulation method.

A pilot tone approach can be used by using one or more subcarriers as pilot tones modulated by predetermined values. For an overlap of T/2, the correlation between adjacent sections of signal spaced T/2, T or higher multiples of T/2 apart can be measured either before or after the receiver transform 16. The symbol timing is adjusted according to the estimated symbol timing error.

For an overlap of T/2, particularly simple algorithms can be used if the relative weightings of pilots in eight successive symbols are +1, 0 ,+1, 0, −1, 0, −1. These give an output which is a linear function of symbol timing error.

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Pilot techniques also have the advantage that they can be used to estimate synchronization error for any initial timing error unlike cyclic prefix synchronisation techniques, which may be limited in their capture range by the length of the cyclic prefix used.

The number of pilots can be varied to achieve an appropriate compromise between timing jitter and loss in bandwidth. More pilots can be used at the start of transmission to increase the initial timing acquisition.

In a similar way. frequency synchronization can be achieved by measuring the change in phase of pilot tones between symbols.

Blind algorithms are another class of symbol synchronisation or frequency synchronization techniques that use characteristics of the incoming signal to detect and correct synchronisation errors. For example, blind algorithms for frequency synchronisation can use techniques that depend on the effect of frequency offset in changing the relative amplitudes of subcarriers which have been modulated in a group. For the case of modulation onto pairs of subcarriers, with no frequency error or distortion, the pair of subcarriers when demodulated have values which are the negative of each other. Frequency offset upsets this balance in a known way, and can thus be used as a basis for frequency synchronization. For example, consider the receiver shown in Fig. 6. In the absence of frequency error or other distortion, $y_k = -y_{k+1}$ for even *k*. This balance is disturbed by frequency error. The metric shown directly below approximates ΔfT for large *N*.

$$\mathrm{Re}\left(\frac{y_{k,i} + y_{k+1,i}}{y_{k,i} - y_{k+1,i}}\right)$$

This metric does not depend on the data used to modulate the subcarrier pair, and hence frequency synchronization can be achieved from the data without pilot tones.

Figs. 8 and 9 respectively show a storage means 18 and equaliser 19, which in combination estimate the transmitted data. The storage means 18 includes a number of storage elements 18A - 18E, each of which is regularly updated each T/2 so that it successively stores data $v_{0,i} \ldots v_{N/2-1,i}$ for use by the equaliser 19. Each T/2, data from one element is passed to the next. The equaliser 19, which completes estimation of the representations of the data from the subcarriers. The equaliser 19 operates on a sequence of output vectors (in Fig. 9, $V_i = v_{0,i} \ldots v_{N/2-1,i}$ and $E_i = e_{0,i} \ldots e_{N/2-1,i}$) from the storage means 18 to output the output data which estimates the input data provided to the transmitter.

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The equaliser shown in Fig. 9 has seven vectors as input, and the storage means 18 has a corresponding number of elements. However, simpler implementations using less vectors V_i, may be suffcient. The number of input vectors needed depends on the degree of distortion in the channel, the amount of overlap and the signal to noise ratio.

In the example shown, a frequency domain equaliser is used in the receiver to recover the transmitted data. However, a time domain equaliser can alternatively be used. A time domain equaliser would operate before the orthogonal transform 16, while the frequency domain equalizer operates after the orthogonal transform 16. Frequency domain equalisers are preferred as relatively simple and effective equalisers can be used as a consequence of the characteristics of modulating representations of data on groups of adjacent subcarriers.

All of the forms of equalization used in one dimensional applications can be adapted to this two-dimensional problem including linear equalization, decision feedback equalization and maximum likelihood sequence estimation (MLSE). When decision feedback equalization is used, error correcting coding across the data in one symbol can be used to reduce the probability of error propagation.

Thus an equaliser of relative simplicity compared with previously suggested equalisers can be used. There are various reasons for this. Firstly, the weighting and adding block at the input reduces the number of inputs to the equalizer. The modulation on groups of subcarriers results in an impulse response which has relatively few significant terms. As a result, simpler equalisers can be designed without significant loss in performance. Furthermore, for the particular case of an overlap of T/2, the form of the interference is independent of the index of the input. This means that for the case of no distortion (that is where the equaliser is only correcting for the overlap of symbols) the structure of the equaliser is symmetric in some respects, which provides an opportunity for relatively simple equaliser structure. Alternative embodiments can be used in which the equaliser has two stages, a fixed equaliser to correct for the deliberately introduced overlap, followed by a simpler adaptive equalizer which corrects for the channel.

The transmitter described above and shown in Fig. 4 uses weighting means 1 to modulate groups of subcarriers with representations of the input data. However, this can alternatively be done by using windowing-based techniques.

Fig. 10 shows a example of a transmitter and receiver which uses windowing methods to modulate subcarriers with representations of the input data. N point orthogonal transforms 3 and 16 having more inputs/outputs than are otherwise necessary are used in combination with exponential roll-off windows 5 and 13. That is, the inputs to the orthogonal transform 3 alternate between zero and input data. The complex exponential window 5 is of the form: $[1 - \exp(j2\pi \cdot l/N)]$.

Fig. 11 shows an alternative approach. N/2 point orthogonal transforms 3 and 16 are used in combination with a cyclic extension 4 and cyclic contraction 14, and exponential roll-off windows 5 and 13. The $N/2$ point orthogonal transform 3 provides a cyclic extension 4 of $N/2$ points. Again the complex window 5 is of the form $[1 - \exp(j2\pi \cdot l/N)]$.

In both cases, the complex window 5, of the form $[1 - \exp(j2\pi \cdot l/N)]$, acts to multiply the l-th value of the transmitter transform output data by a factor of $[1 - \exp(j2\pi \cdot l/N)]$ before further processing.

The cyclic contraction required in the receiver is preferably achieved by simply performing an element-by-element summation of the data points indexed $0 \ldots N/2-1$ with those data points indexed $N/2 \ldots N-1$. In this case, the number of data values is doubled and then halved by the cyclic extension 4 and cyclic contraction 14 respectively.

In both cases, the exponential roll-off window 13 in the receiver are preferably the complex conjugate of the exponential roll-off window 5 in the transmitter.

The embodiments described above modulate the subcarriers with representations of the input data that are respectively equal positive and negative values of each input data. However, it is possible and in some cases desirable (such, as in the presence of strong multipath interference) to use higher order schemes which use a greater number of representations of the input data.

By extension of the transmitter and receiver shown in Figs. 4 and 6 respectively, cubic cancellation can be achieved by using with the following transmitter weighting and receiver weighting coefficients:

$$p_0 = 1,\ p_1 = -2,\ p_2 = 1$$

$$q_0 = 1,\ q_1 = -2,\ q_2 = 1$$

This corresponds with the polynomial:

$$1 - 2x - x^2$$

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Similarly, quintic cancellation can be achieved with the following transmitter weighting coefficients and receiver weighting coefficients for $W = 4$.

$$p_0 = 1,\ p_1 = -3,\ p_2 = 3,\ p_3 = -1$$

$$q_0 = 1,\ q_1 = -3,\ q_2 = 3,\ q_3 = -1$$

This corresponds with the polynomial:

$$1 - 3x + 3x^2 - x^3$$

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Still higher order schemes can be provided by generating further representations which are used to modulate a correspondly greater number of subcarriers. Representations can be generated in accordance with the polynomial $(1-x)^{W-1}$. The coefficients can be provided by expanding this polynomial.

Fig. 12 shows an embodiment which uses three representations of each input data to modulate a group of subcarriers. The weightings p_0, p_1, p_2 are complex coefficients of the polynomial $(1-x)^{W-1}$ where $W = 3$. The factors $K_0 \ldots K_{D-1}$ are complex factors which scale the representations provided by weightings p_0, p_1, p_2, allowing for relative changes in amplitude and phase between the values modulated on respective subcarriers.

The values of $K_0 \ldots K_{D-1}$ can be made unity. However, in some cases, it is desirable to modify amplitude and phase by modifying $K_0 \ldots K_{D-1}$ .For example, it may be necessary to adjust the amplitude of certain channels to equalise the signal. Similarly, it may be necessary to adjust the phase of the signal to modify its power characteristics.

If complex pre-weighting factors $K_0 \ldots K_{D-1}$ in the transmitter, as shown Fig. 12, it is appropriate to also use corresponding post-weighting factors $L_0 \ldots L_{D-1}$ in the receiver. For example, it may be appropriate to use post-weight factors $L_0 \ldots L_{D-1}$ which are the inverse, or complex conjugate, of the pre-weighting factors $K_0 \ldots K_{D-1}$ in the transmitter. Of course, pre-weighting and post-weighting factors can be used in other cases, for example, when only two weight factors are used.

Fig. 13 shows a further embodiment of a transmitter having a generalised mapping between input data ($d_{0,i} \ldots d_{D-1,i}$) and weighted input data ($a_{0,i} \ldots a_{P-1,i}$). ICI cancellation is achieved in the transmitter so that the individual decoded weighted output data ($z_{0,i} \ldots z_{P-1,i}$) in the receiver is relatively free of ICI and is used to estimate the input data ($d_{0,i} \ldots d_{D-1,i}$).

Most simply, mapping of the input data ($d_{0,i} \ldots d_{D-1,i}$) onto weighted input data ($a_{0,i} \ldots a_{P-1,i}$) can be arranged so that there is a direct mapping from the x possible values that the input data d can take (typically this would be a power of 2, ie 2, 4, 8, 16 etc) to x combinations chosen to fit some particular criterion. For example, the criterion could be maximum Euclidean distance to minimise error rate or some combination of limitation of power roll-off, insensitivity to frequency offset, minimise peak-to-mean power ratio. Any other criterion, or compromise between competing criteria could be chosen as appropriate for a given application.

As an example, consider the case of grouping in fours in the transmitter. There are various ways that this can be achieved.

To achieve linear cancellation with four carriers, the carriers must be weighted with the coefficients of

$$(1-x)^2(g_0+g_1x)$$

where g_0 and g_1 are any values including complex values. Different values of input data can be mapped to different combinations of g_0 and g_1. For example, g_0 and g_1 could be allowed to take values 1+j, 1-j, -1+j, -1-j. Then there are sixteen possible combinations and 4 bits could be mapped onto the four carriers.

At the receiver z_0 is used as an estimate of g_0 and z_3 is used as an estimate of g_1. The linear component of ICI is cancelled in each of these values. However, the performance with respect to noise is not optimal due to the asymmetry between transmitter and receiver, and the consequent breakdown of the matched filter

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condition.

Alternatively, the mappings can be changed from symbol period to symbol period in a predetermined way to implement codes in some respects analogous to trellis code modulation. Preferably, $2x$ combinations could be defined, but only x would be allowable in any particular symbol period.

As mentioned earlier, subcarriers can be multiplied by factors to adjust peak-to-mean power. Wilkinson and Jones ("Minimisation of the Peak to Mean envelope Power Ratio of Multicarrier Transmission Schemes by Block Coding", *IEEE 45th Vehicular Technology Conference*, Chicago, 1995, pp.825-829) discusses how coding can be used to reduce peak-to-mean power in OFDM systems.

Of course, it is not necessary that each input data has the same number of representations. For example, it may be desirable to provide modulate a greater number of representations of input data on subcarriers near the frequency boundaries of the signal. This has the advantage of a steeper power spectrum roll-off at the frequency domain boundaries of the signal. Similarly, it is not necessary to use all of the subcarriers. Some subcarriers can be left unmodulated, as may be preferred in some embodiments.

In alternative embodiments, it is possible to have each (or alternating) subcarriers modulated by values which are a summation of representations of different input data. While this reduces the number of subcarriers for a given number of input data, it is generally not found to be advantageous and is accordingly not preferred.

Fig. 14 to Fig. 16 are performance graphs of particular embodiments compared with comparable conventional systems.

Fig. 14 is a scatterplot of symbols received for a typical prior art OFDM system with 64 subcarriers.

Fig. 15 is a scatterplot of symbols received for an embodiment of the present invention that uses 64 subcarriers and linear cancellation.

Fig. 16 is a scatterplot of symbols received for an embodiment that uses 64 subcarriers and cubic cancellation.

Fig. 17 is a graph showing the signal to ICI noise ratio of an embodiment of the invention compared with the signal to ICI noise ratio of a conventional OFDM system.

Fig. 18 includes two graphs - an upper graph showing the power spectrum roll-off of a conventional OFDM system, and a lower graph showing the power spectrum roll-off of a typical embodiment.

OFDM systems can use various different schemes to modulate subcarriers, such as phase shift keying (PSK) or quadrature amplitude modulation (QAM). Embodiments of the invention do not depend on the mapping of data to be transmitted to input data ($d_{0,i}$ ... $d_{D-1,i}$) and are therefore applicable to forms of modulation that can be used with OFDM generally.

Preferably a Fourier-based frequency transform, such as a DFT, or a discrete cosine or sine transform (DCT or DST) is used in the described embodiments. However, it is not necessary that an orthogonal transform be of this type as there are a number of other orthogonal transforms that may also be suitable, such as the Walsh transform, the Hadamard transform and the various types of wavelet transforms.

The orthogonal transform can in certain embodiments make use of fact that data which modulates particular subcarriers is correlated, and similarly in the receiver it is the weighted and summed outputs that are important. Consequently, the computational complexity involved in transformation calculations can be significantly reduced by the use of appropriate algorithms which assume that certain data points are correlated.

This involves appropriate exploitation of techniques for reducing the complexity of Fast Fourier Transform (FFT) calculations, for example, the decimation in time and decimation in frequency algorithms.

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To illustrate this point, the discrete Fourier algorithm is usually expressed as a linear summation of complex exponential terms:

$$X(k) = \sum_{n=0}^{N-1} x(n) W_N^{kn}$$

where

$$W_N = \exp(-j2\pi/N)$$

If *x*(*n*) is an input sequence in which alternate terms are the negative of each other, then the expression above can be rearranged:

$$\begin{aligned} X(k) &= \sum_{\substack{n=0 \\ n \text{ even}}}^{N-1} x(n) W_N^{kn} - W_N^{k} \sum_{\substack{n=0 \\ n \text{ even}}}^{N-1} x(n) W_N^{kn} \\ &= \left(1 - W_N^{k}\right) \sum_{\substack{n=0 \\ n \text{ even}}}^{N-1} x(n) W_N^{kn} \end{aligned}$$

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This allows an N point calculation to be reduced to an N/2 point calculation, followed by multiplication by a constant factor.

Further to the above embodiments, there are a variety of systems that are not limited to a single transmitter and a single receiver. A number of transmitters may be provided to provide a broadcast coverage of a signal. Similarly, a number of receivers can be provided for multiple users. In such broadcast systems there are also known to be systems whereby different transmitters and receivers may be assigned to different subsets of subcarriers. Some of these ideas are outlined in a recent paper by A.C. Caswell ("Multicarrier Transmission in a Mobile Radio Channel", *Electronic Letters*, 10th October 1996 Vol 32 pp. 1962-1963).

It will be understood that the invention disclosed and defined in this specification extends to all alternative combinations of two or more of the individual features mentioned or evident from the text or drawings. All of these different combinations constitute various alternative aspects of the invention.

THE CLAIMS DEFINING THE INVENTION ARE AS FOLLOWS

1 A method of transmitting data in a multicarrier modulation system in which transform pairs allow communication using multiple subcarriers, the method including:

modulating representations of data on groups of subcarriers; and

introducing a predetermined amount of intersymbol interference between symbols;

wherein the modulation includes a modulation operation in which the data is effectively multiplied with weighting factors, before inverse transformation.

2 A method as claimed in claim 1, wherein the modulation includes a weighting operation in which the data is multiplied with weighting factors, before inverse transformation.

3 A method as claimed in claim 1, wherein the modulation includes a windowing operation in which the data is multiplied with a complex window, after inverse transformation.

4 A method as claimed in any one of claims 1 to 3, wherein the groups of subcarriers include non-overlapping sets of M adjacent subcarriers, and the M respective representations are integer multiples of the data, the integers corresponding with coefficients of the expanded polynomial expression $(1-x)^{M-1}$.

5 A method as claimed in any one of claims 1 to 4, wherein the data is modulated on a pair of adjacent subcarriers, and the representations of the data are multiples of 1 and -1.

6 A method as claimed in any one of claims 1 to 5, wherein introducing

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intersymbol interference includes overlapping successive symbols to a predetermined extent by delaying and summing groups of samples of the symbols.

7 A method as claimed in claim 6, wherein successive symbols are overlapped with each other by half a symbol period.

8 A method as claimed in any one of claims 1 to 7, wherein inverse transformation includes using mathematical correlations between representations of the data to reduce computational and/or memory requirements of hardware on which the inverse transformation is determined.

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9 A method as claimed in claim 8, wherein said inverse transformation is performed at least in part by a complex windowing operation.

10 A method as claimed in any one of claims 1 to 9, wherein subcarriers are modulated by a summation of representations of different data.

11 A method as claimed in claim 10, wherein each subcarrier is modulated by the difference between adjacent data.

12 A method as claimed in any one of claims 1 to 11, further including providing pilot tones on subcarriers.

13 A method as claimed in claim 12, wherein relative values of the pilot tones on successive symbols follows the sequence +1, 0, +1, 0, -1, 0, -1, 0.

14 A method of receiving data in a multicarrier modulation system in which transform pairs allow communication using multiple subcarriers, the method including:

demodulating data from representations of data on groups of subcarriers; and

removing a predetermined amount of intersymbol interference between symbols;

wherein the demodulation includes a demodulation operation in which the representations are effectively multiplied with weighting factors, and the results summed after or, as part of transformation.

15 A method as claimed in claim 14, wherein the demodulation includes a weighting and summing operation in which the representations are multiplied with weighting factors, and the results summed after or, as part of transformation.

16 A method as claimed in claim 14, wherein the demodulation includes a complex windowing operation in which the representations are multiplied with a complex window, before transformation.

17 A method as claimed in any one of claims 14 to 16, wherein the groups of subcarriers include non-overlapping sets of M adjacent subcarriers, and the M respective representations are integer multiples of the data, the integers corresponding with coefficients of the expanded polynomial expression $(1-x)^{M-1}$.

18 A method as claimed in any one of claims 14 to 17, wherein the data is effectively modulated on a pair of adjacent subcarriers, and the representations of the data are multiples of 1 and -1.

19 A method as claimed in any one of claims 14 to 18, wherein removing intersymbol interference between symbols includes removing a predetermined amount of intersymbol interference caused by overlapping symbols to a predetermined extent.

20 A method as claimed in claim 19, wherein the predetermined amount of intersymbol interference is caused by overlapping symbols by half a symbol period.

21 A method as claimed in any one of claims 14 to 20, wherein removing intersymbol interference between symbols includes delaying groups of samples so that each transformation operates on samples which reduce the error rate.

22 A method as claimed in any one of claims 14 to 21, wherein removing intersymbol interference between symbols includes frequency domain equalisation.

23 A method as claimed in claim 22, wherein the frequency domain equalisation involves relatively few significant terms owing to the use of groups of subcarriers modulated by representations of the data.

24 A method as claimed in claim 21, wherein removing intersymbol interference between symbols includes frequency domain equalisation in which the form of calculations involved are the same for each subcarrier.

25 A method as claimed in any one of claims 21 to 24, wherein frequency domain equalisation operates on the output of the demodulation.

26 A method as claimed in any one of claims 14 to 25, wherein removing intersymbol interference includes a fixed operation for removing intersymbol interference caused by introduction of a predetermined amount of intersymbol interference, and an adaptive operation for removing intersymbol interference caused by reasons other than introduction of a predetermined amount of intersymbol interference.

27 A method as claimed in any one of claims 14 to 26, wherein transformation involves using mathematical correlations between representations of the

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data to reduce computational and/or memory requirements of hardware on which the transformation is determined.

28 A method as claimed in claim 27, wherein said transformation is performed at least in part by a complex windowing removing operation.

29 A method as claimed in any one of claims 14 to 28, further including symbol synchronisation involving measuring the correlation between sections of signal, in which pilot tones are provided on subcarriers.

30 A method as claimed in claim 29, wherein relative values of the pilot tones on successive symbols follows the sequence +1, 0, +1, 0, -1, 0, -1, 0.

31 A method as claimed in any one of claims 14 to 30, further including frequency synchronisation involving measuring phase changes between the pilot tones provided on subcarriers.

32 A method as claimed in any one of claims 14 to 30, further including frequency synchronisation involving calculating a metric having a known dependence on frequency offset.

33 A method as claimed in claim 32, wherein the metric approximates the multiplicative product of frequency offset and symbol period, and is calculated using the expression:

$$\mathrm{Re}\left(\frac{y_{k,i} + y_{k+1,i}}{y_{k,i} - y_{k+1,i}}\right)$$

34 A transmitter suitable for transmitting data in a multicarrier modulation system in which transform pairs allow communication using multiple subcarriers, the transmitter including:

means for modulating representations of data on groups of subcarriers; and

means for introducing a predetermined amount of intersymbol interference between symbols;

wherein the modulation includes a modulation operation in which the data is effectively multiplied with weighting factors, before inverse transformation.

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35 A transmitter as claimed in claim 34, wherein the modulation includes a weighting operation in which the data is multiplied with weighting factors, before inverse transformation.

36 A transmitter as claimed in claim 34, wherein the modulation includes a complex windowing operation in which the data is multiplied with a complex window, after inverse transformation.

37 A receiver suitable for receiving data in a multicarrier modulation system in which transform pairs allow communication using multiple subcarriers, the receiver including:

means for demodulating data from representations of data on groups of subcarriers; and

means for removing a predetermined amount of intersymbol interference between symbols;

wherein the demodulation includes a demodulation operation in which the representations are effectively multiplied with weighting factors, and the results summed, after or as part of transformation.

suggest
write
+ format

38 A receiver as claimed in claim 37, wherein the demodulation includes a weighting and summing operation in which the representations are

multiplied with weighting factors, and the results summed, after or as part of transformation.

39 A receiver as claimed in claim 37, wherein the demodulation includes a complex windowing operation in which the representations are multiplied with a complex window, before transformation.

40 A multicarrier modulation system incorporating one or more transmitters as claimed in any one of claims 34 to 36 and one or more receivers as claimed in any one of claims 37 to 39, wherein the transmitters and receivers are adapted to communicate with each other.

41 A multicarrier modulation system as claimed in claim 40, wherein the weighting factors respectively used in the transmitter and the receiver have equal relative values, or the complex windows respectively used in the transmitter and the receiver are the complex conjugate of each other.

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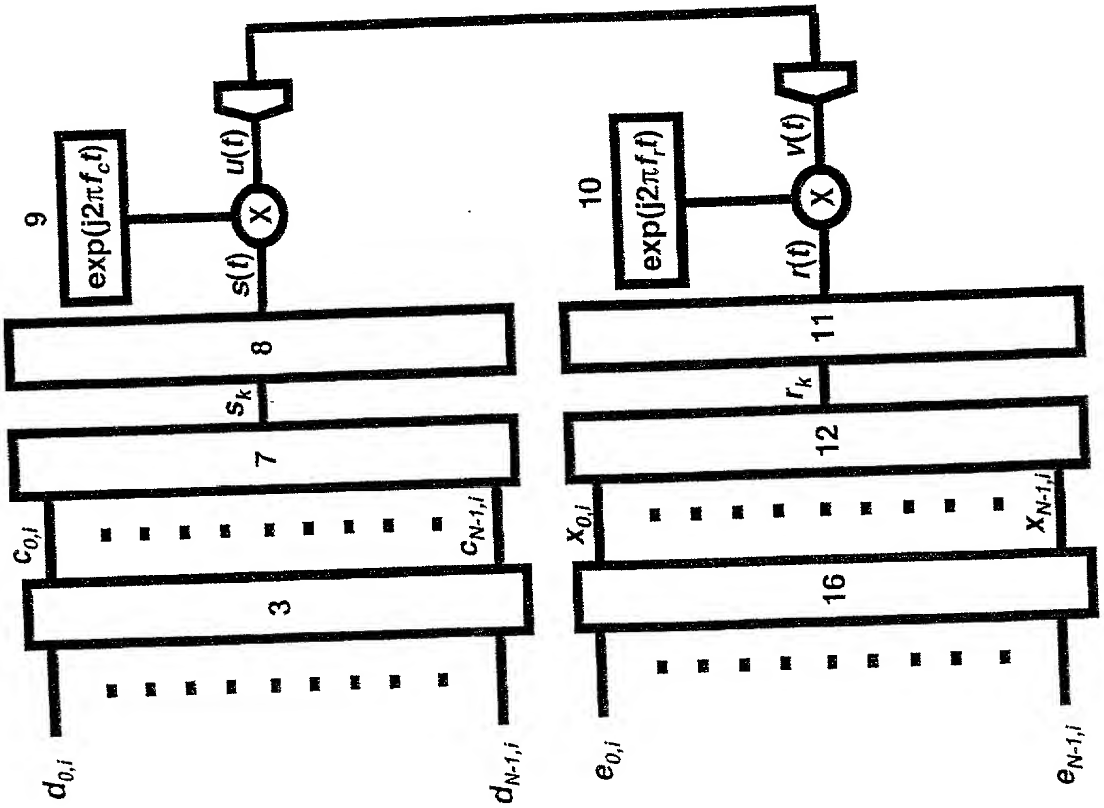

$d_{0,i}$
$d_{N-1,i}$
3
$c_{0,i}$
$c_{N-1,i}$
7
s_k
8
$s(t)$
X
$u(t)$
9
$\exp(j2\pi f_c t)$
$e_{0,i}$
$e_{N-1,i}$
16
$x_{0,i}$
$x_{N-1,i}$
12
r_k
11
$r(t)$
X
$v(t)$
10
$\exp(j2\pi f_r t)$

FIG. 1

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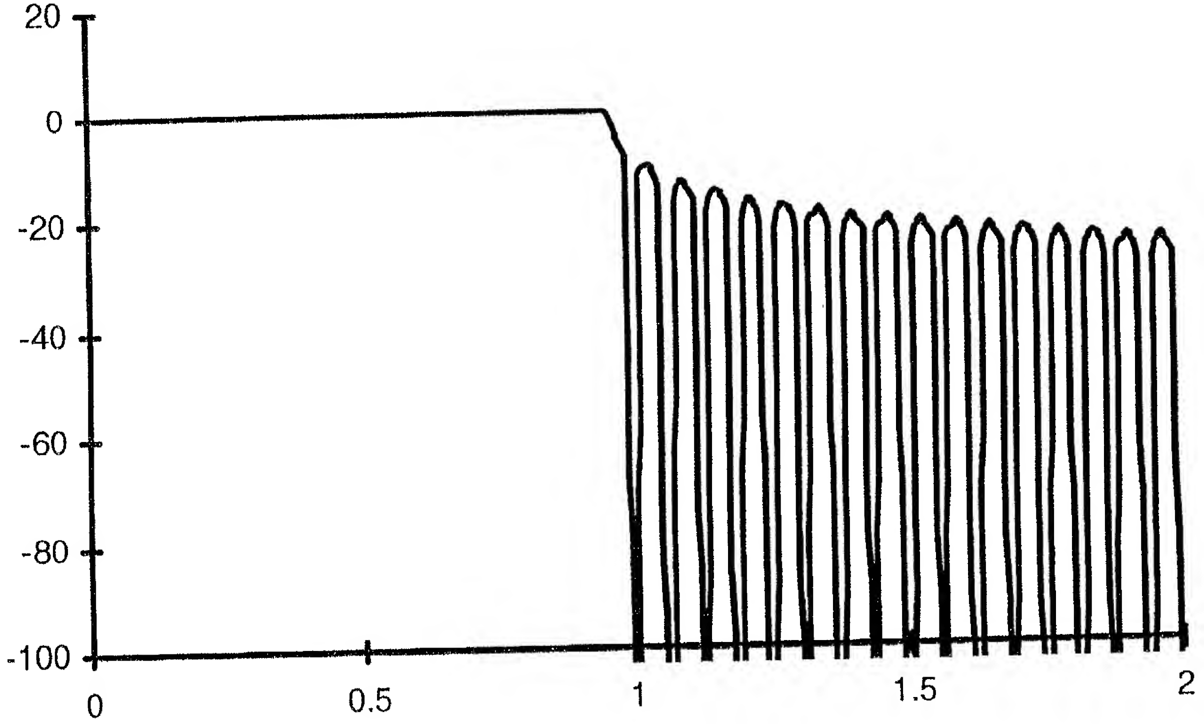

FIG. 2

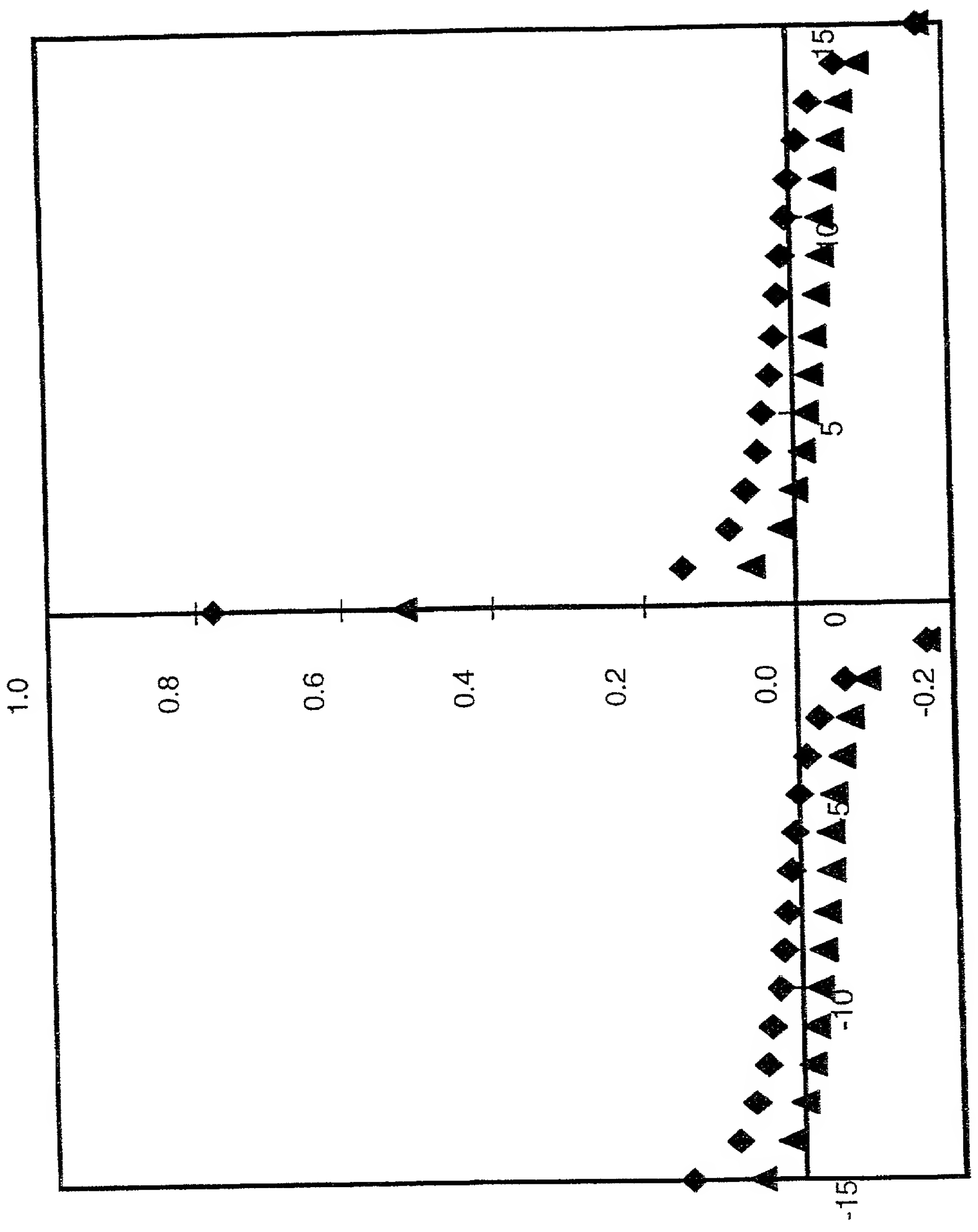

FIG. 3

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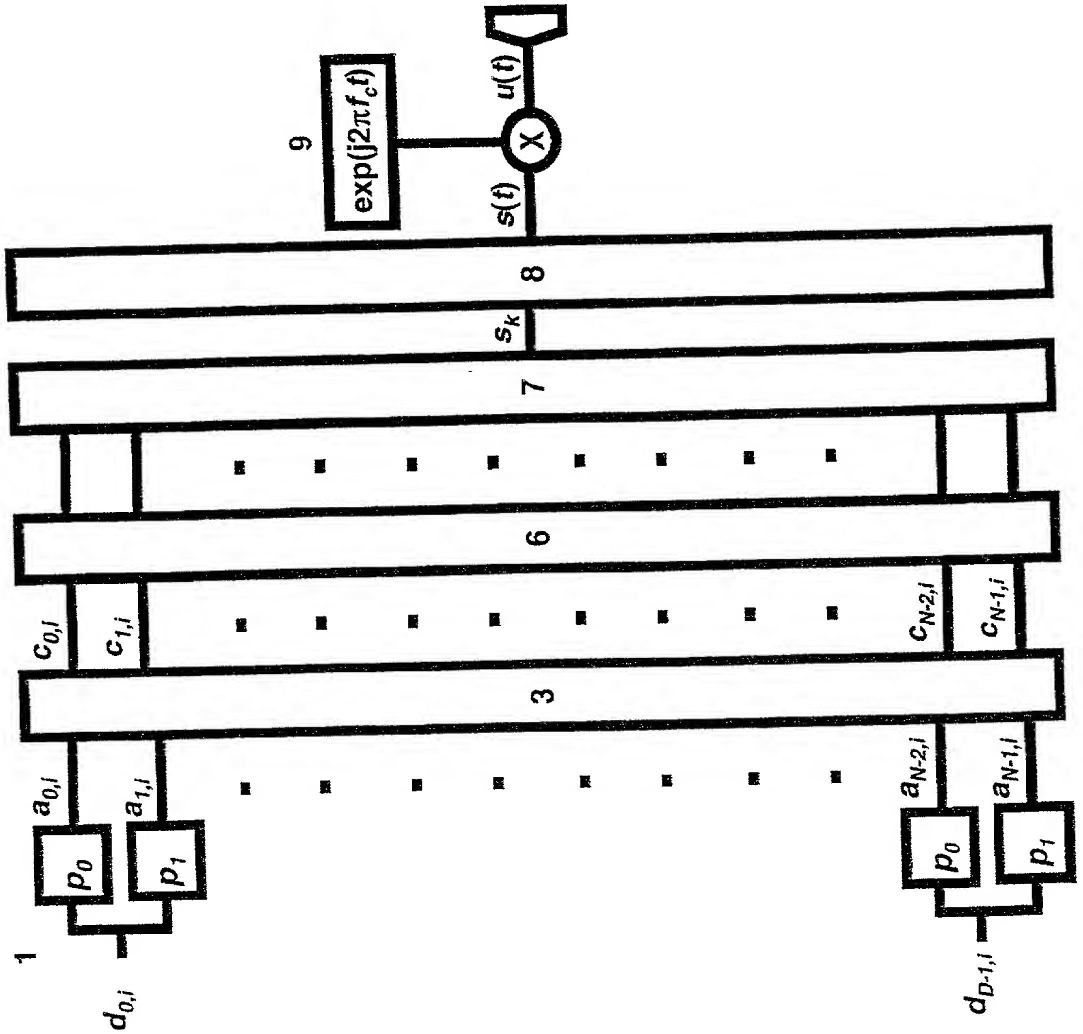
FIG. 4


9
$\exp(j2\pi f_c t)$
$u(t)$
X
$s(t)$
8
s_k
7
6
$c_{0,i}$
$c_{1,i}$
$c_{N-2,i}$
$c_{N-1,i}$
3
$a_{0,i}$
$a_{1,i}$
$a_{N-2,i}$
$a_{N-1,i}$
p_0
p_1
p_0
p_1
1
$d_{0,i}$
$d_{D-1,i}$

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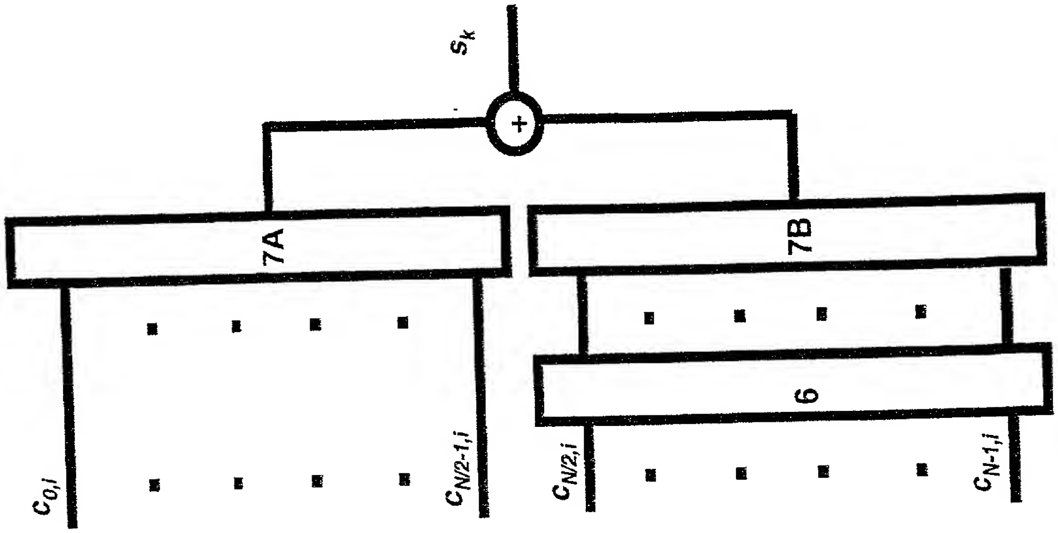
s_k
+
7A
7B
6
$c_{0,i}$
$c_{N/2-1,i}$
$c_{N/2,i}$
$c_{N-1,i}$

FIG. 5

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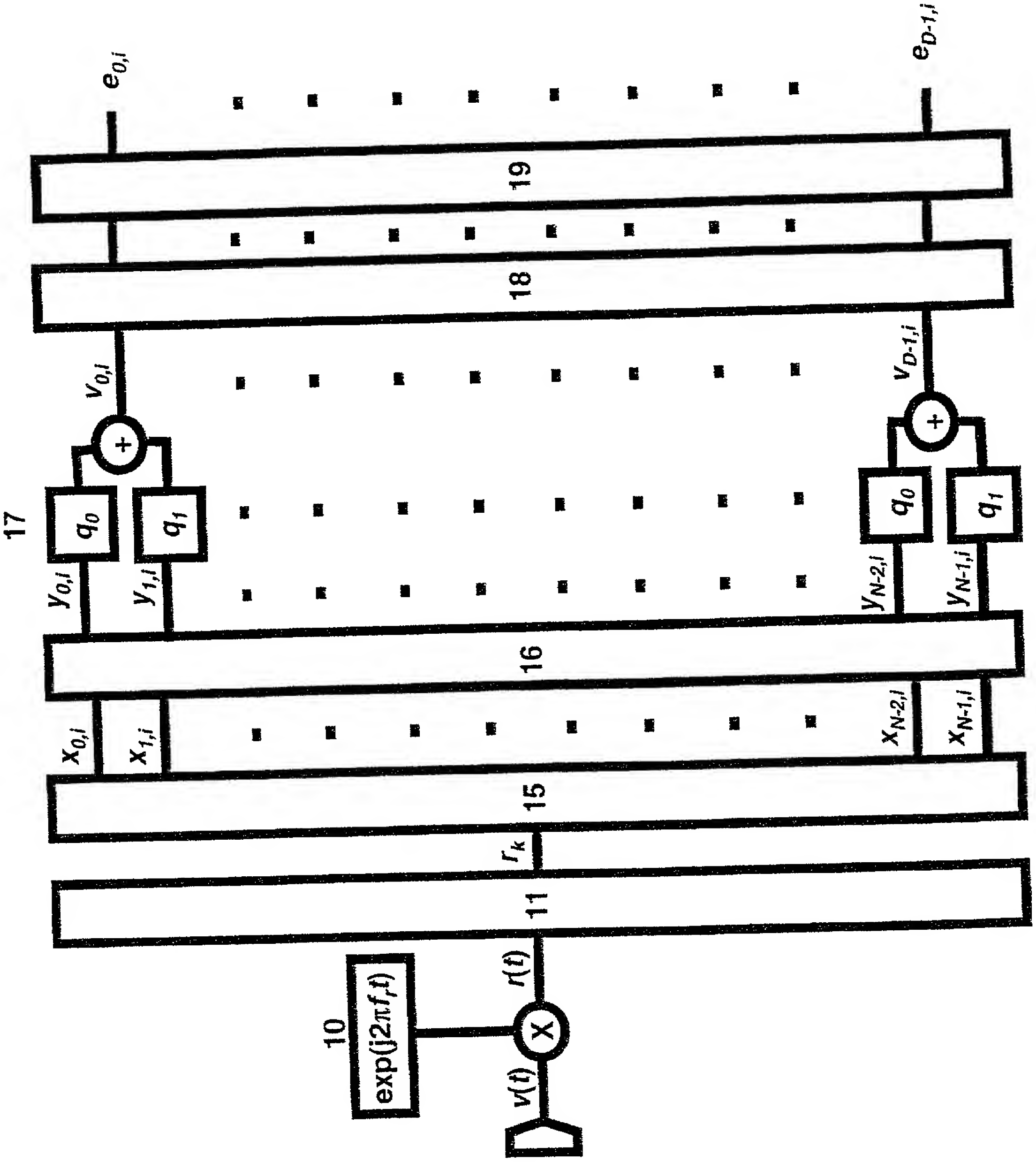
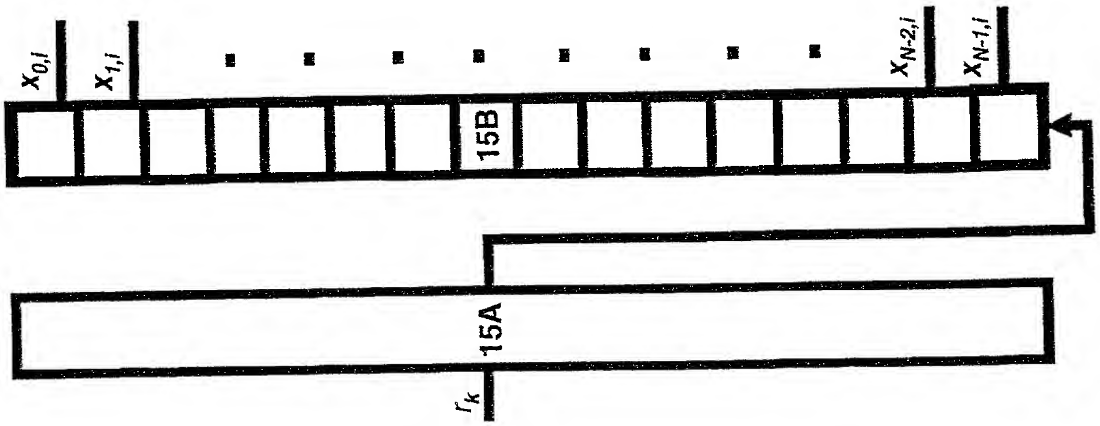

$e_{0,i}$
$e_{D-1,i}$
19
18
$v_{0,i}$
$v_{D-1,i}$
+
17
q_0
q_1
$y_{0,i}$
$y_{1,i}$
$y_{N-2,i}$
$y_{N-1,i}$
16
$x_{0,i}$
$x_{1,i}$
$x_{N-2,i}$
$x_{N-1,i}$
15
r_k
11
$r(t)$
X
$v(t)$
10
$\exp(j2\pi f_r t)$

FIG. 6

FIG. 7


$x_{0,i}$
$x_{1,i}$
$x_{N-2,i}$
$x_{N-1,i}$
15B
15A
r_k

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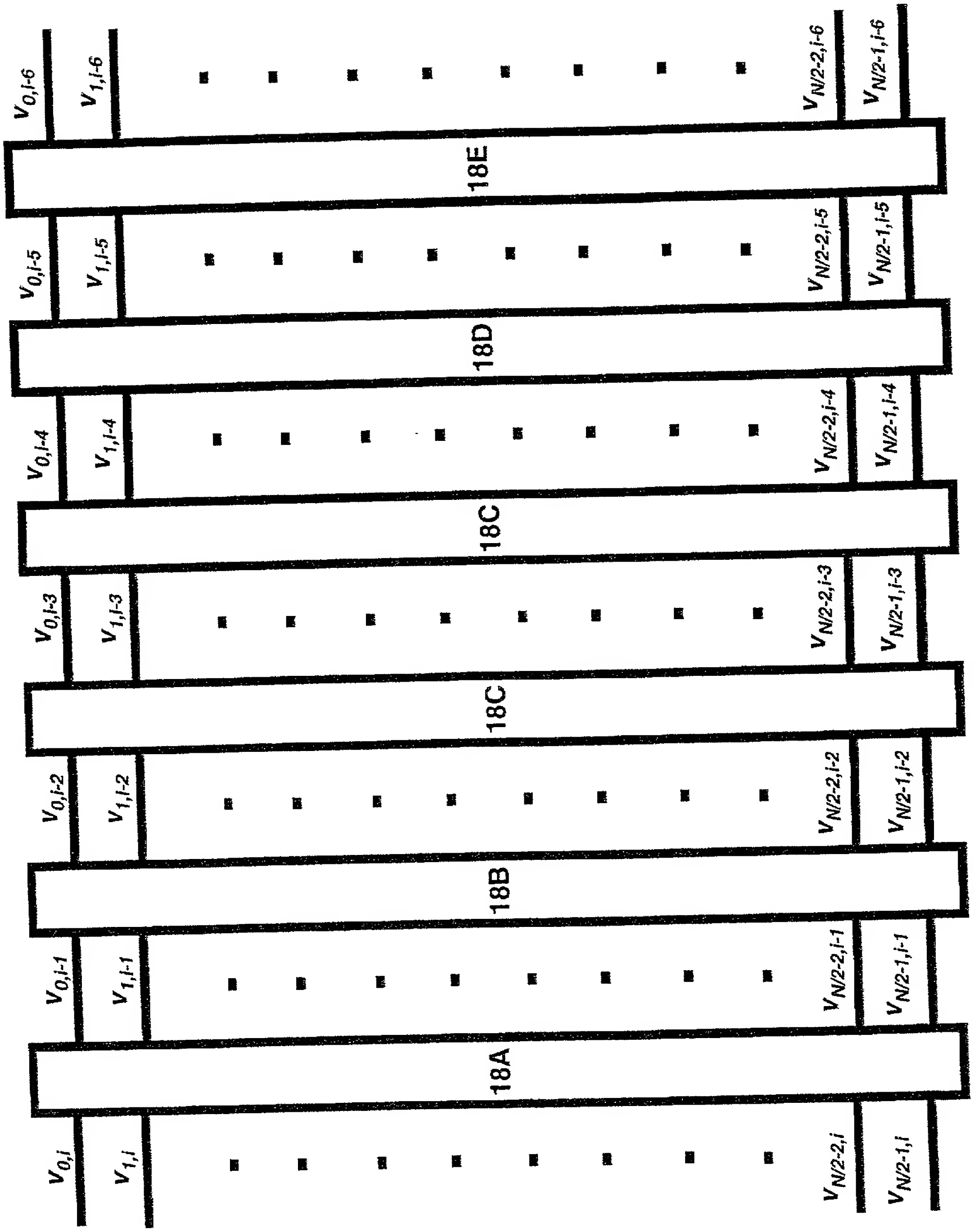
$v_{0,i-6}$
$v_{1,i-6}$
$v_{N/2-2,i-6}$
$v_{N/2-1,i-6}$
18E
$v_{0,i-5}$
$v_{1,i-5}$
$v_{N/2-2,i-5}$
$v_{N/2-1,i-5}$
18D
$v_{0,i-4}$
$v_{1,i-4}$
$v_{N/2-2,i-4}$
$v_{N/2-1,i-4}$
18C
$v_{0,i-3}$
$v_{1,i-3}$
$v_{N/2-2,i-3}$
$v_{N/2-1,i-3}$
18C
$v_{0,i-2}$
$v_{1,i-2}$
$v_{N/2-2,i-2}$
$v_{N/2-1,i-2}$
18B
$v_{0,i-1}$
$v_{1,i-1}$
$v_{N/2-2,i-1}$
$v_{N/2-1,i-1}$
18A
$v_{0,i}$
$v_{1,i}$
$v_{N/2-2,i}$
$v_{N/2-1,i}$

FIG. 8

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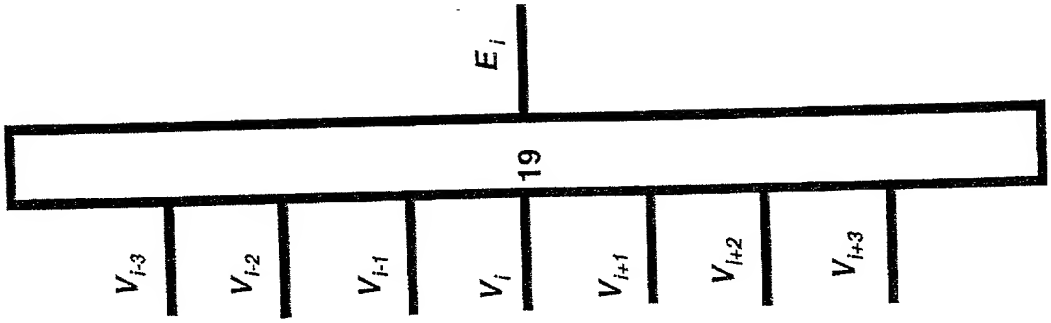
FIG. 9


E_i
19
V_{i-3}
V_{i-2}
V_{i-1}
V_i
V_{i+1}
V_{i+2}
V_{i+3}

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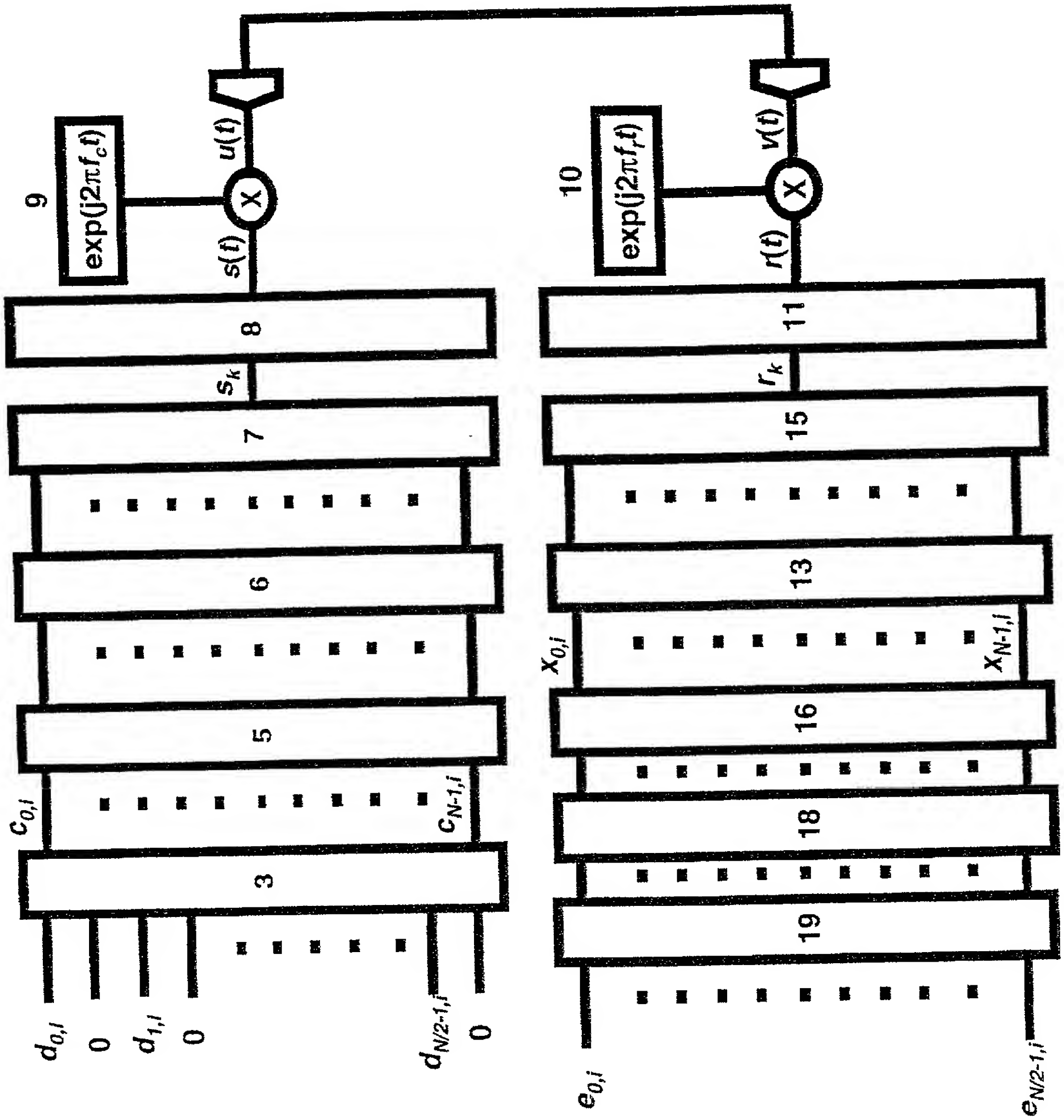

9
exp(j2πf_c t)
s(t)
u(t)
X
8
s_k
7
6
5
c_{0,l}
c_{N-1,l}
3
d_{0,l}
0
d_{1,l}
0
d_{N/2-1,l}
0
10
exp(j2πf_r t)
r(t)
v(t)
X
11
r_k
15
13
x_{0,l}
x_{N-1,l}
16
18
19
e_{0,l}
e_{N/2-1,l}

FIG. 10

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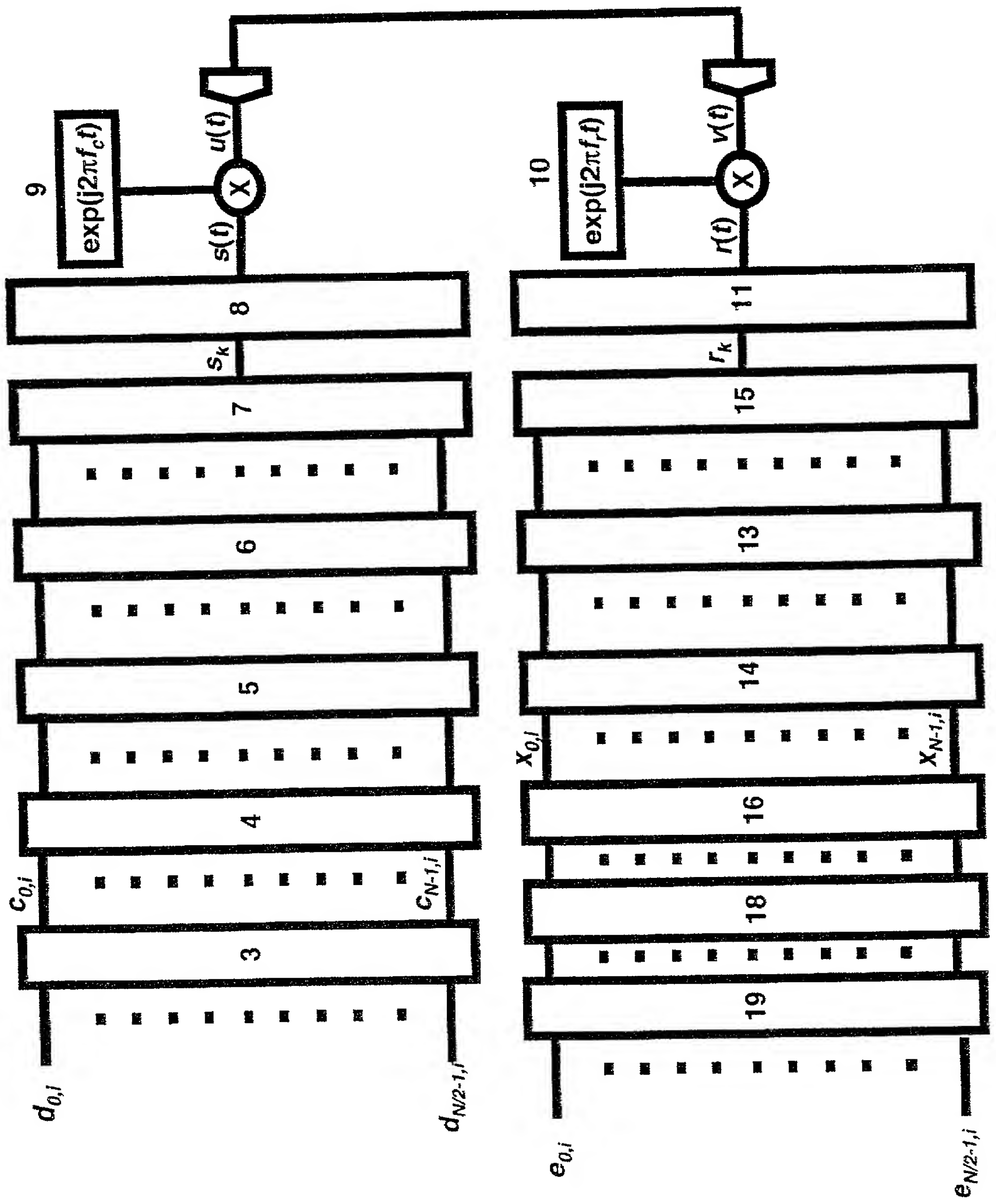
9
exp(j2πf_c t)
X
u(t)
s(t)
8
s_k
7
6
5
4
c_{0,i}
c_{N-1,i}
3
d_{0,i}
d_{N/2-1,i}
10
exp(j2πf_r t)
X
v(t)
r(t)
11
r_k
15
13
14
x_{0,i}
x_{N-1,i}
16
18
19
e_{0,i}
e_{N/2-1,i}

FIG. 11

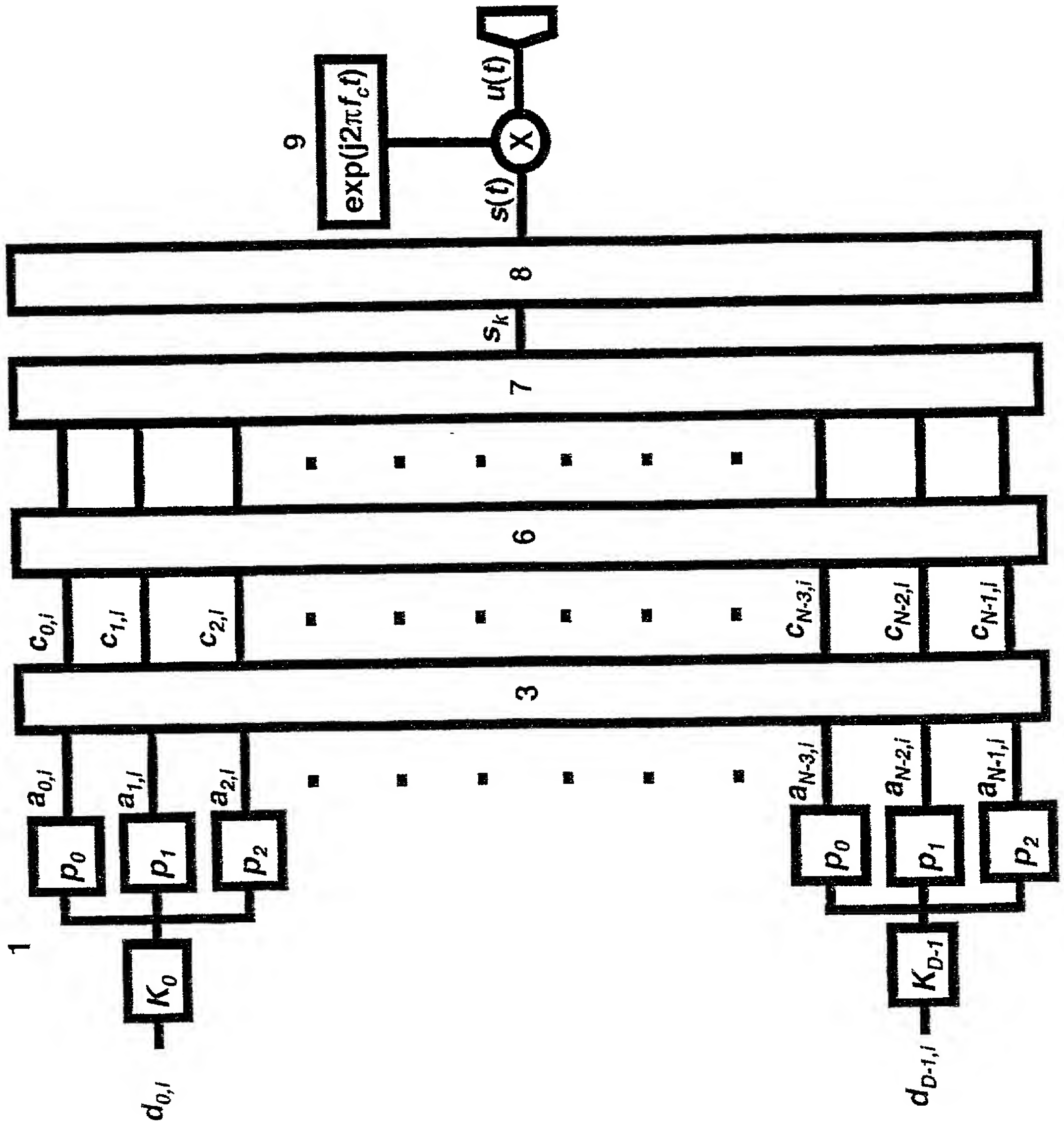
9
exp(j2πf_c t)
u(t)
X
s(t)
8
s_k
7
6
c_{0,l}
c_{1,l}
c_{2,l}
c_{N-3,l}
c_{N-2,l}
c_{N-1,l}
3
a_{0,l}
a_{1,l}
a_{2,l}
a_{N-3,l}
a_{N-2,l}
a_{N-1,l}
p_0
p_1
p_2
p_0
p_1
p_2
1
K_0
K_{D-1}
d_{0,l}
d_{D-1,l}

FIG. 12

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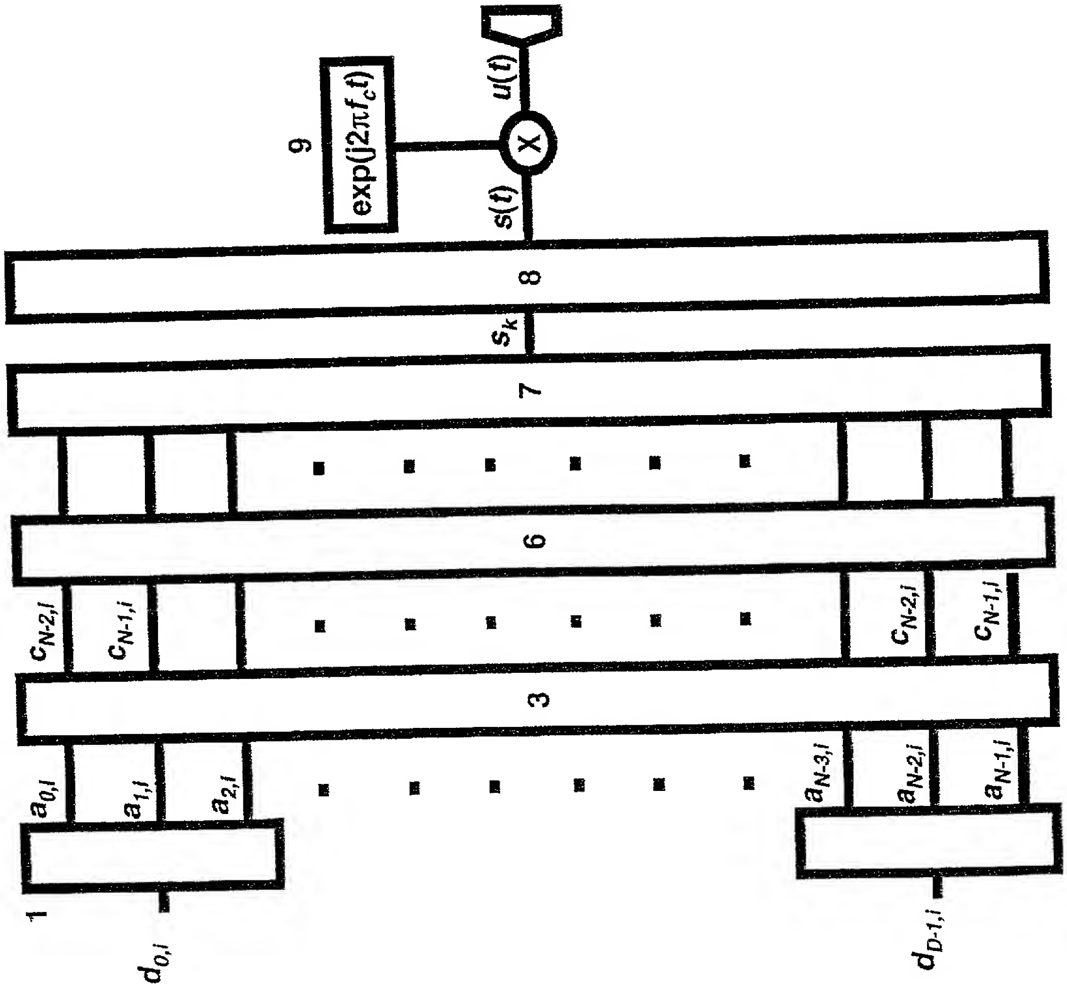
9
exp(j2πf_ct)
u(t)
X
s(t)
8
s_k
7
6
c_{N-2,l}
c_{N-1,l}
c_{N-2,l}
c_{N-1,l}
3
a_{0,l}
a_{1,l}
a_{2,l}
a_{N-3,l}
a_{N-2,l}
a_{N-1,l}
1
d_{0,l}
d_{D-1,l}

FIG. 13

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FIG. 14

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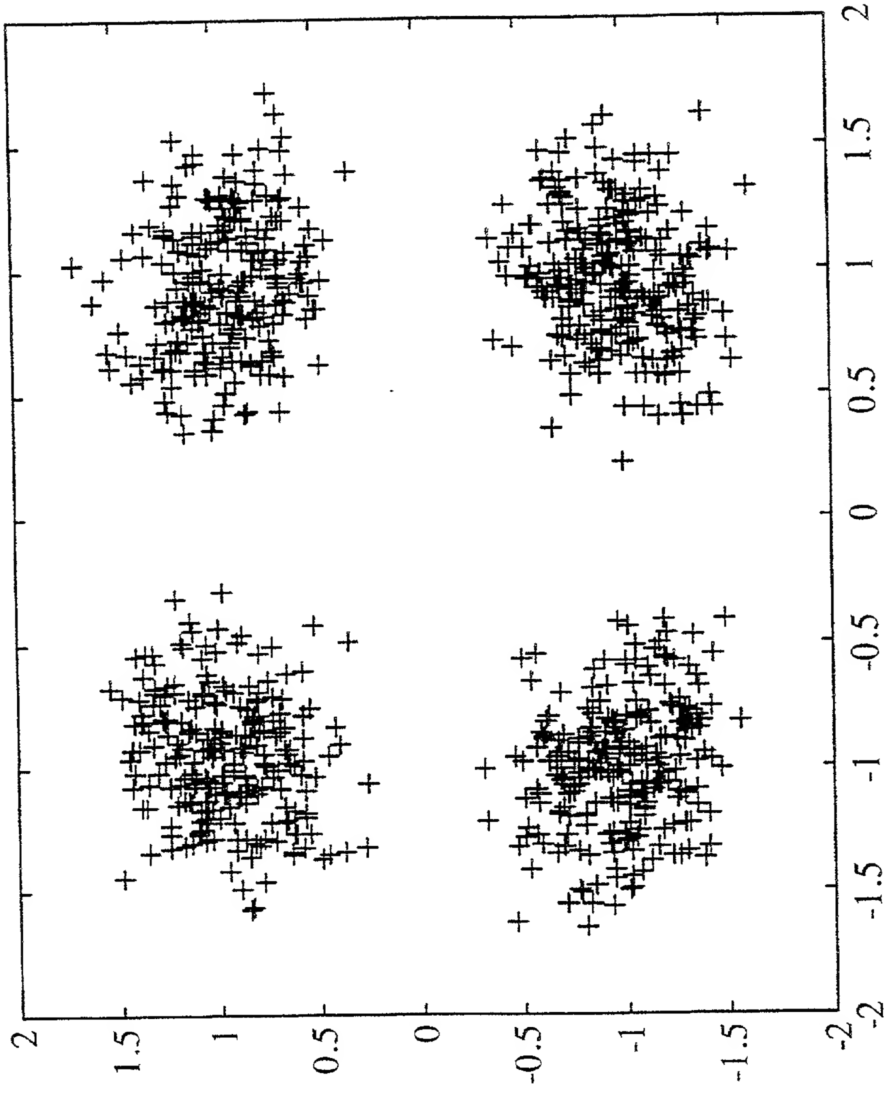

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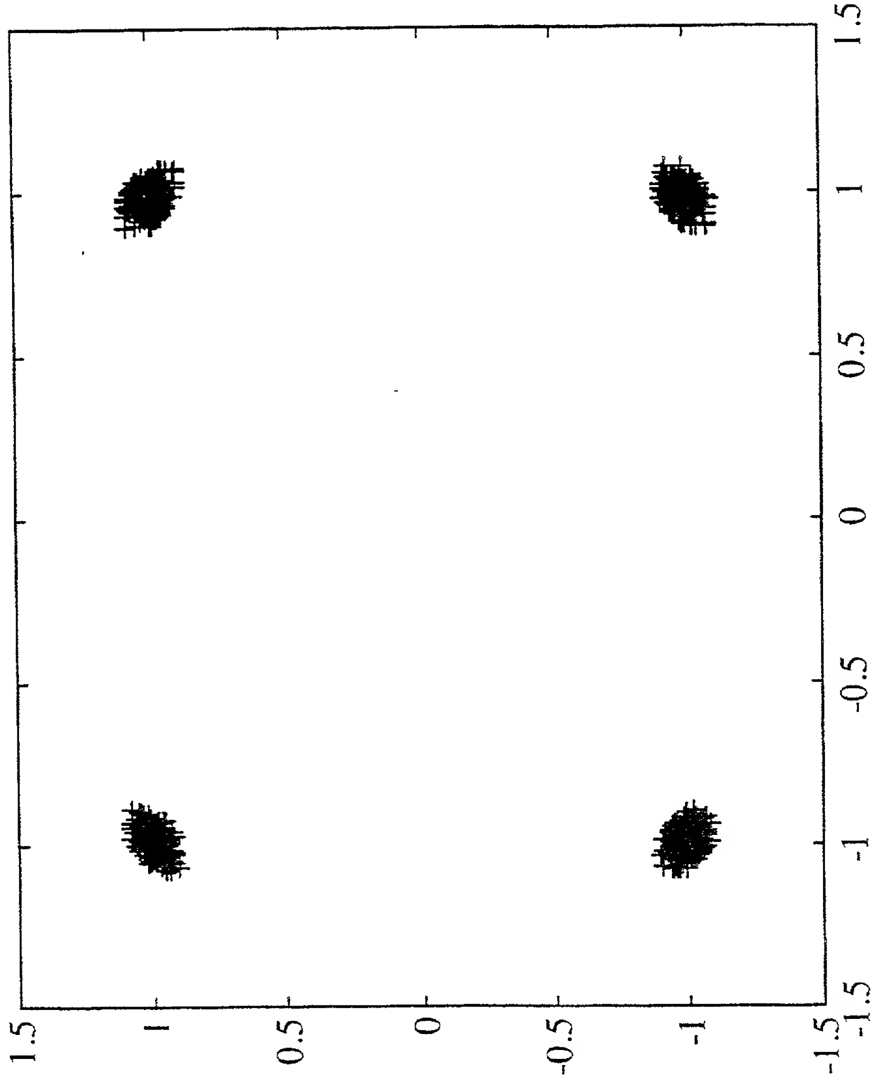

FIG. 15

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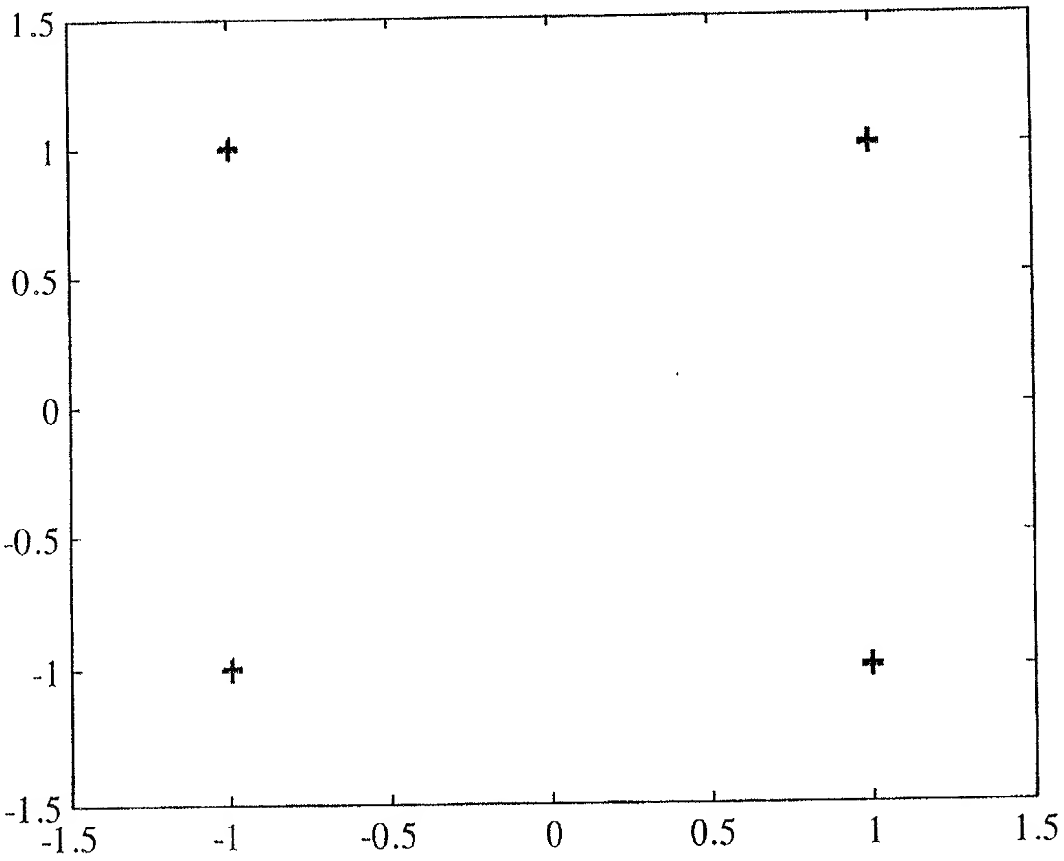

FIG. 16

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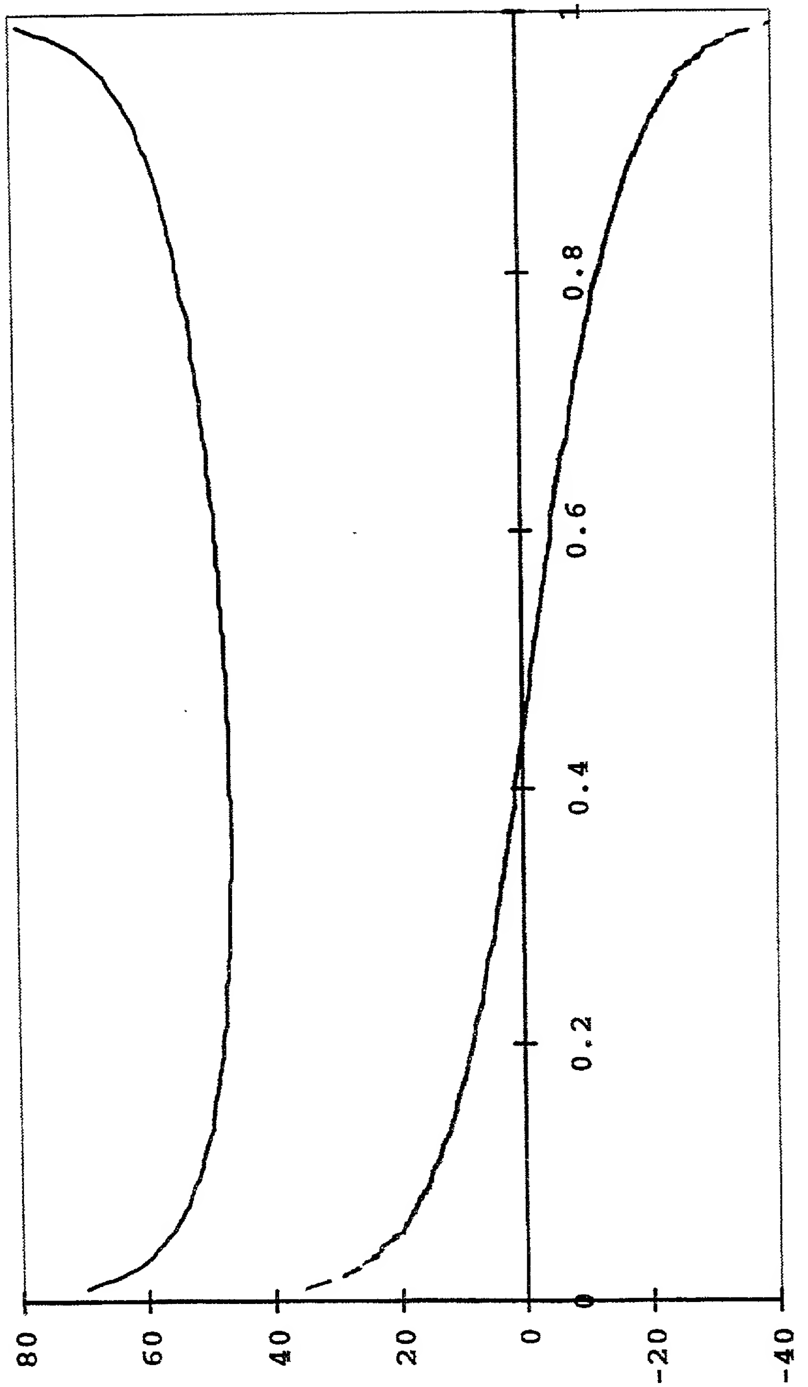

FIG. 17

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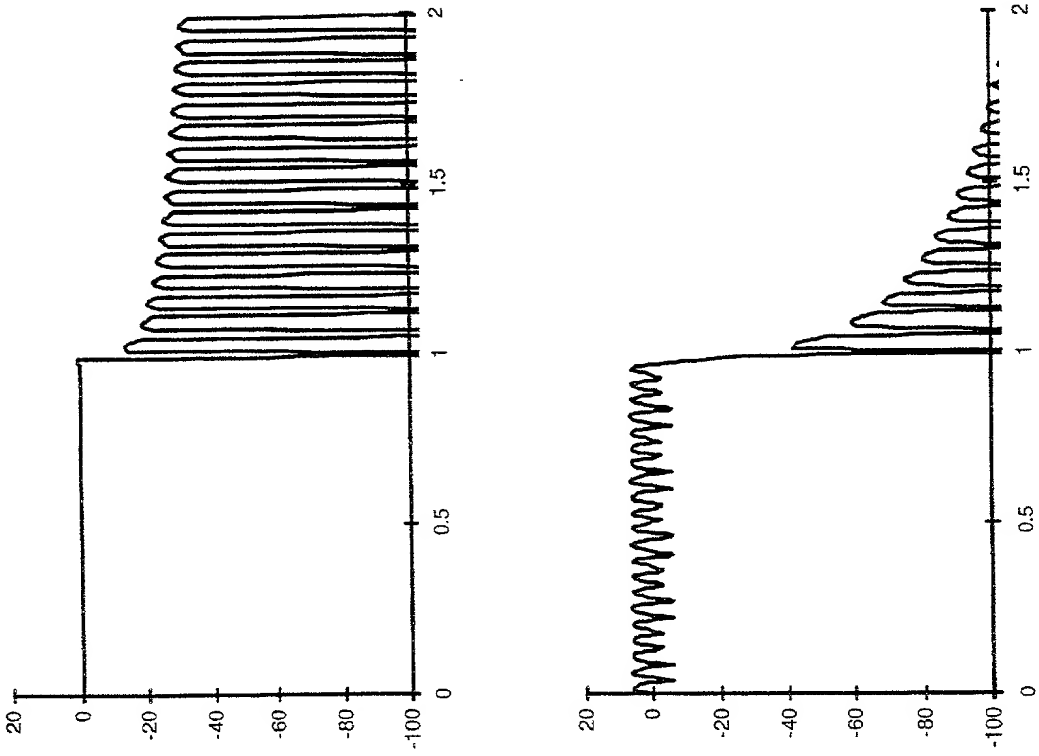
FIG. 18



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33874 PCT/USA

BAKER & BOTTS L.L.P
FILE NO.: RBH

COMBINED DECLARATION AND POWER OF ATTORNEY

(Original, Design, National Stage of PCT, Divisional, Continuation or C-I-P Application)

As a below named inventor, I hereby declare that:
My residence, post office address and citizenship are as stated below next to my name; I believe I am the original, first and sole inventor (if only one name is listed below) or an original, first and joint inventor (if plural names are listed below) of the subject matter which is claimed and for which a patent is sought on the invention entitled:

This declaration is of the following type:

- ☐ original
- ☐ design
- ☒ national stage of PCT.
- ☐ divisional
- ☐ continuation
- ☐ continuation-in-part (C-I-P)

the specification of which: *(complete (a), (b), or (c))*

(a) ☒ is attached hereto.
(b) ☐ was filed on as Application Serial No. and was amended on *(if applicable).*
(c) ☐ was described and claimed in PCT International Application No. filed on and was amended on *(if applicable).*

Acknowledgement of Review of Papers and Duty of Candor

I hereby state that I have reviewed and understand the contents of the above identified specification, including the claims, as amended by any amendment referred to above.

I acknowledge the duty to disclose information which is material to the patentability of the subject matter claimed in this application in accordance with Title 37, Code of Federal Regulations § 1.56.

☐ In compliance with this duty there is attached an information disclosure statement. 37 CFR 1.98.

Priority Claim

I hereby claim foreign priority benefits under Title 35, United States Code, § 119(a)-(d) of any foreign application(s) for patent or inventor's certificate or of any PCT International Application(s) designating at least one country other than the United States of America listed below and have also identified below any foreign application(s) for patent or inventor's certificate or any PCT International Application(s) designating at least one country other than the United States of America filed by me on the same subject matter having a filing date before hat of the application on which priority is claimed

(complete (d) or (e))

d) ☐ no such applications have been filed.
e) ☒ such applications have been filed as follows:

PRIOR FOREIGN/PCT APPLICATION(S) FILED WITHIN 12 MONTHS (6 MONTHS FOR DESIGN) PRIOR TO SAID APPLICATION				
COUNTRY	APPLICATION NO	DATE OF FILING (day month, year)	DATE OF ISSUE (day, month, year)	PRIORITY CLAIMED UNDER 35 USC 119
				☐ YES NO ☐
				☐ YES NO ☐
				☐ YES NO ☐
ALL FOREIGN APPLICATION[S], IF ANY, FILED MORE THAN 12 MONTHS (6 MONTHS FOR DESIGN) PRIOR TO SAID APPLICATION				
AUSTRALIA	PP 3698	26/05/1998		☒ YES NO ☐
AUSTRALIA	PP 4250	22/06/1998		☒ YES NO ☐
AUSTRALIA	PCT/AU99/00409	26/05/1999		☒ YES NO ☐

Claim for Benefit of Prior U.S. Provisional Application(s)

I hereby claim the benefit under Title 35, United States Code, § 119(e) of any United States provisional application(s) listed below:

Provisional Application Number	Filing Date

Claim for Benefit of Earlier U.S./PCT Application(s) under 35 U.S.C. 120

(complete this part only if this is a divisional, continuation or C-I-P application)

I hereby claim the benefit under Title 35, United States Code, § 120 of any United States application(s) or PCT international application(s) designating the United States of America that is/are listed below and, insofar as the subject matter of each of the claims of this application is not disclosed in the prior application(s) in the manner provided by the first paragraph of Title 35, United States Code § 112, I acknowledge the duty to disclose information as defined in Title 37, Code of Federal Regulations, § 1.56 which occurred between the filing date of the prior application(s) and the national or PCT international filing date of this application:

(Application Serial No.) (Filing Date) (Status) (patented, pending, abandoned)

(Application Serial No.) (Filing Date) (Status) (patented, pending, abandoned)

Power of Attorney

As a named inventor, I hereby appoint Dana M. Raymond, Reg. No. 18,540, Frederick C. Carver, Reg. No. 17,021; Francis J. Hone Reg. No. 18,662; Joseph D. Garon, Reg. No. 20,420; Arthur S. Tenser, Reg. No. 18,839; Ronald B. Hildreth, Reg. No. 19,498; Thomas R. Nesbitt, Jr., Reg. No. 22,075; Robert Neuner, Reg. No. 24,316; Richard G. Berkley, Reg. No. 25,465; Richard S. Clark, Reg. No. 26,154; Bradley B. Geist, Reg. No. 27,551; James J. Maune, Reg. No. 26,946; John D. Murnane, Reg. No. 29,836, Henry Tang, Reg. No. 29,705, Robert C. Scheinfeld, Reg. No. 31,300, John A. Fogarty, Jr., Reg. No. 22,348, Louis S. Sorell, Reg. No. 32,439 and Rochelle K. Seide Reg. No. 32,300 of the firm of BAKER & BOTTS, L.L.P., with offices at 30 Rockefeller Plaza, New York, New York 10112, as attorneys o prosecute this application and to transact all business in the Patent and Trademark Office connected therewith

SEND CORRESPONDENCE TO: BAKER & BOTTS, L.L.P. 30 ROCKEFELLER PLAZA, NEW YORK, N.Y. 10112 CUSTOMER NUMBER: 21003	DIRECT TELEPHONE CALLS TO: BAKER & BOTTS, L.L.P. (212) 705-5000

I hereby declare that all statements made herein of my own knowledge are true and that all statements made n information and belief are believed to be true; and further that these statements were made with the knowledge hat willful false statements and the like so made are punishable by fine or imprisonment, or both, under Section

1001 of Title 18 of the United States Code and that such willful false statements may jeopardize the validity of the application or any patent issued thereon.

FULL NAME OF SOLE OR FIRST INVENTOR	LAST NAME ARMSTRONG	FIRST NAME JEAN	MIDDLE NAME	
RESIDENCE & CITIZENSHIP AUSTRALIA	CITY NORTH BALWYN	STATE or FOREIGN COUNTRY VICTORIA	COUNTRY OF CITIZENSHIP AUSTRALIA	
POST OFFICE ADDRESS	POST OFFICE ADDRESS 44 LONGVIEW ROAD	CITY NORTH BALWYN	STATE or COUNTRY VICTORIA	ZIP CODE 3104
DATE 14 November 2000	SIGNATURE OF INVENTOR			
FULL NAME OF SECOND JOINT INVENTOR, IF ANY	LAST NAME	FIRST NAME	MIDDLE NAME	
RESIDENCE & CITIZENSHIP	CITY	STATE or FOREIGN COUNTRY	COUNTRY OF CITIZENSHIP	
POST OFFICE ADDRESS	POST OFFICE ADDRESS	CITY	STATE or COUNTRY	ZIP CODE
DATE	SIGNATURE OF INVENTOR			
FULL NAME OF THIRD JOINT INVENTOR, IF ANY	LAST NAME	FIRST NAME	MIDDLE NAME	
RESIDENCE & CITIZENSHIP	CITY	STATE or FOREIGN COUNTRY	COUNTRY OF CITIZENSHIP	
POST OFFICE ADDRESS	POST OFFICE ADDRESS	CITY	STATE or COUNTRY	ZIP CODE
DATE	SIGNATURE OF INVENTOR			
FULL NAME OF FOURTH JOINT INVENTOR, IF ANY	LAST NAME	FIRST NAME	MIDDLE NAME	
RESIDENCE & CITIZENSHIP	CITY	STATE or FOREIGN COUNTRY	COUNTRY OF CITIZENSHIP	
POST OFFICE ADDRESS	POST OFFICE ADDRESS	CITY	STATE or COUNTRY	ZIP CODE
DATE	SIGNATURE OF INVENTOR			
FULL NAME OF FIFTH JOINT INVENTOR, IF ANY	LAST NAME	FIRST NAME	MIDDLE NAME	
RESIDENCE & CITIZENSHIP	CITY	STATE or FOREIGN COUNTRY	COUNTRY OF CITIZENSHIP	
POST OFFICE ADDRESS	POST OFFICE ADDRESS	CITY	STATE or COUNTRY	ZIP CODE
DATE	SIGNATURE OF INVENTOR			
FULL NAME OF SIXTH JOINT INVENTOR, IF ANY	LAST NAME	FIRST NAME	MIDDLE NAME	
RESIDENCE & CITIZENSHIP	CITY	STATE or FOREIGN COUNTRY	COUNTRY OF CITIZENSHIP	
POST OFFICE ADDRESS	POST OFFICE ADDRESS	CITY	STATE or COUNTRY	ZIP CODE
DATE	SIGNATURE OF INVENTOR			

FULL NAME OF SEVENTH JOINT INVENTOR, IF ANY	LAST NAME	FIRST NAME	MIDDLE NAME	
RESIDENCE & CITIZENSHIP	CITY	STATE or FOREIGN COUNTRY	COUNTRY OF CITIZENSHIP	
POST OFFICE ADDRESS	POST OFFICE ADDRESS	CITY	STATE or COUNTRY	ZIP CODE
DATE	SIGNATURE OF INVENTOR			

Check proper box(es) for any added page(s) forming a part of this declaration

[ ] Signature for ninth and subsequent joint inventors. Number of pages added ________.

[ ] Signature by administrator(trix), executor(trix) or legal representative for deceased or incapacitated inventor. Number of pages added ________________________________.

[ ] Signature for inventor who refuses to sign, or cannot be reached, by person authorized under 37 CFR 1.47. Number of pages added ________________.

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